

Searches for Dark Matter at the LHC

PANIC 2021
5 September 2021

Katharina Behr

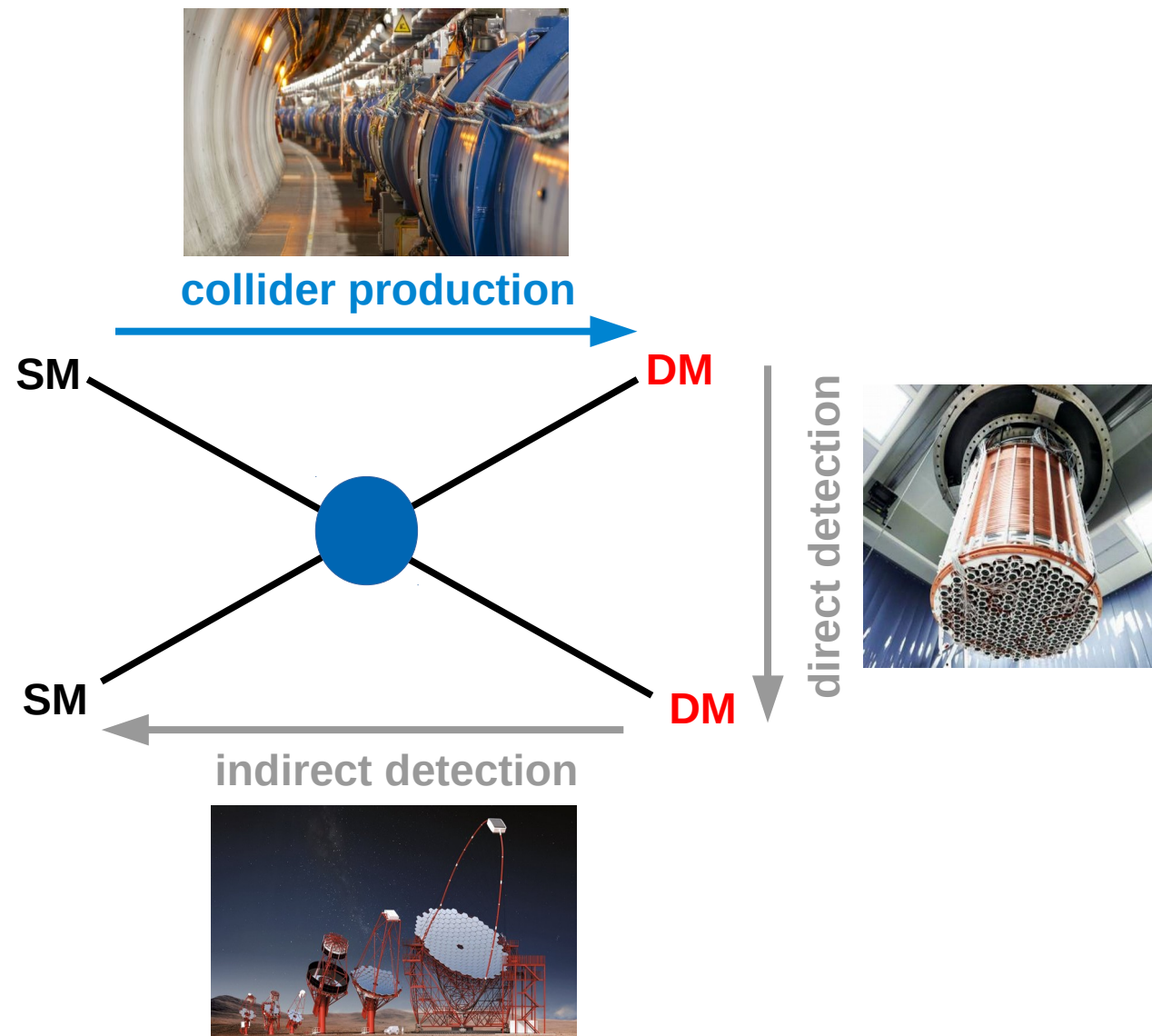


Collider production of dark matter

- > Potentially sensitive to nature of DM-SM interaction
- > Caveat: can only detect DM indirectly via missing transverse momentum (MET)

Transverse momentum conservation:

$$p_{\text{T}}^{\text{miss}} = - \sum p_{\text{T}}^{\text{visible}}$$



Overview of recent ATLAS and CMS results

> Individual searches

- | | | |
|----------------------------------|---|---|
| • MET+jet | ATLAS: Phys. Rev. D 103, 112006, | CMS: arxiv:2107.13021 |
| • MET+y | ATLAS: JHEP 02 (2021) 226 | |
| • MET+Z(l) | ATLAS: ATLAS-CONF-2021-029, | CMS: EPJC 81 (2021) 13 |
| • MET+h(bb) | ATLAS: arxiv:2108.13391 | |
| • MET+tW | ATLAS: arxiv:2011.09308 (accepted by EPJC) | |
| • MET+tt | ATLAS: JHEP 04 (2021) 165, EPJC 80 (2020) 737 | CMS: arxiv:2107.10892 |
| • MET+s(WW) | ATLAS: PRL 126 (2021) 121802 | CMS: CMS-PAS-EXO-20-013 |
| • Strongly coupled hidden sector | | CMS: CMS-PAS-EXO-19-020 |

> Combinations and summaries (preliminary)

- | | | |
|---------------------|---|---|
| • Simplified models | ATLAS: ATL-PHYS-PUB-2021-006, | CMS: SummaryPlotsEXO13TeV |
| • Higgs portal | ATLAS: ATLAS-CONF-2020-052 | |
| • 2HDM+a | ATLAS: ATLAS-CONF-2021-036 | |

Disclaimers:

Only searches with full Run 2 dataset directly targeting DM

Not including SUSY results (see talks by [H. Pacey](#) and [H. Hiltbrand](#))

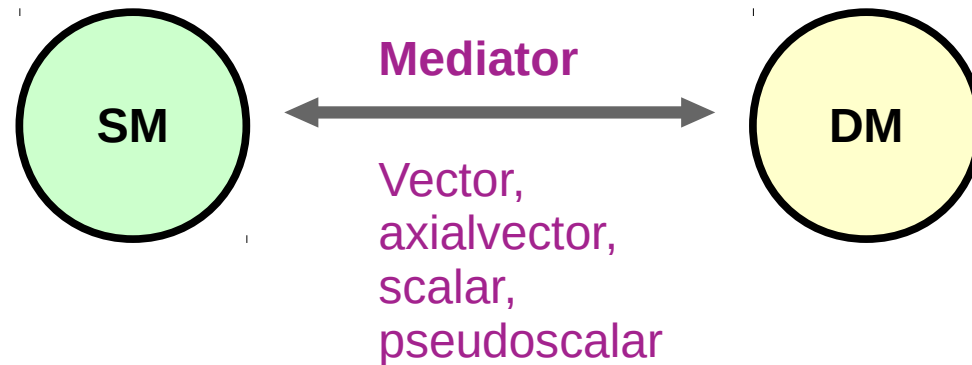
What is the nature of the DM-SM interaction?



Disclaimer: Focus on WIMP hypothesis of DM here

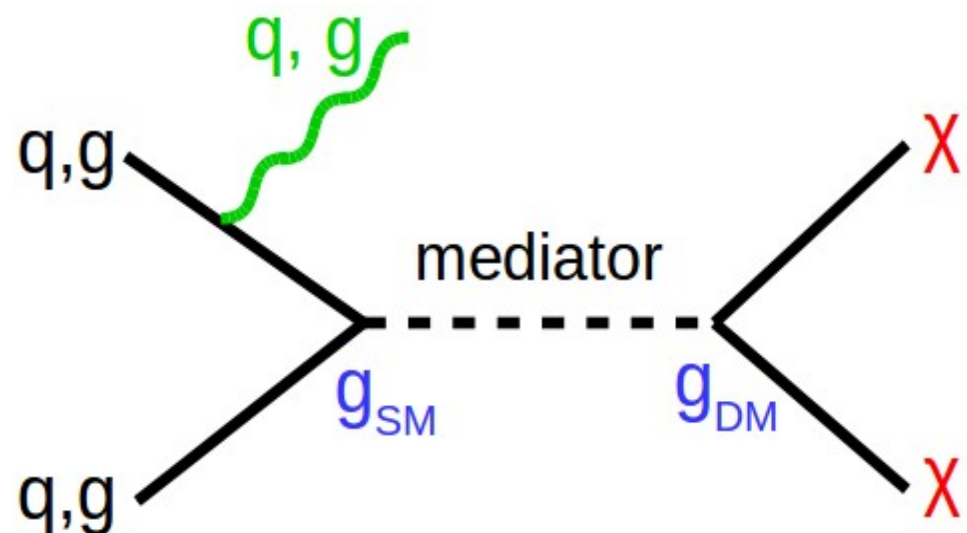
A. Simplified models

- > Simplified models: few particles, few parameters
- > Useful for comparisons between experiments (benchmarks)
- > Limited range of signatures



s-channel mediators

- > Aim to detect invisible decays of the mediator to DM → missing transverse momentum (MET)
- > Problem: Need a hard object to **trigger** on the event
- > Solution: **initial-state radiation (ISR)**



Signatures

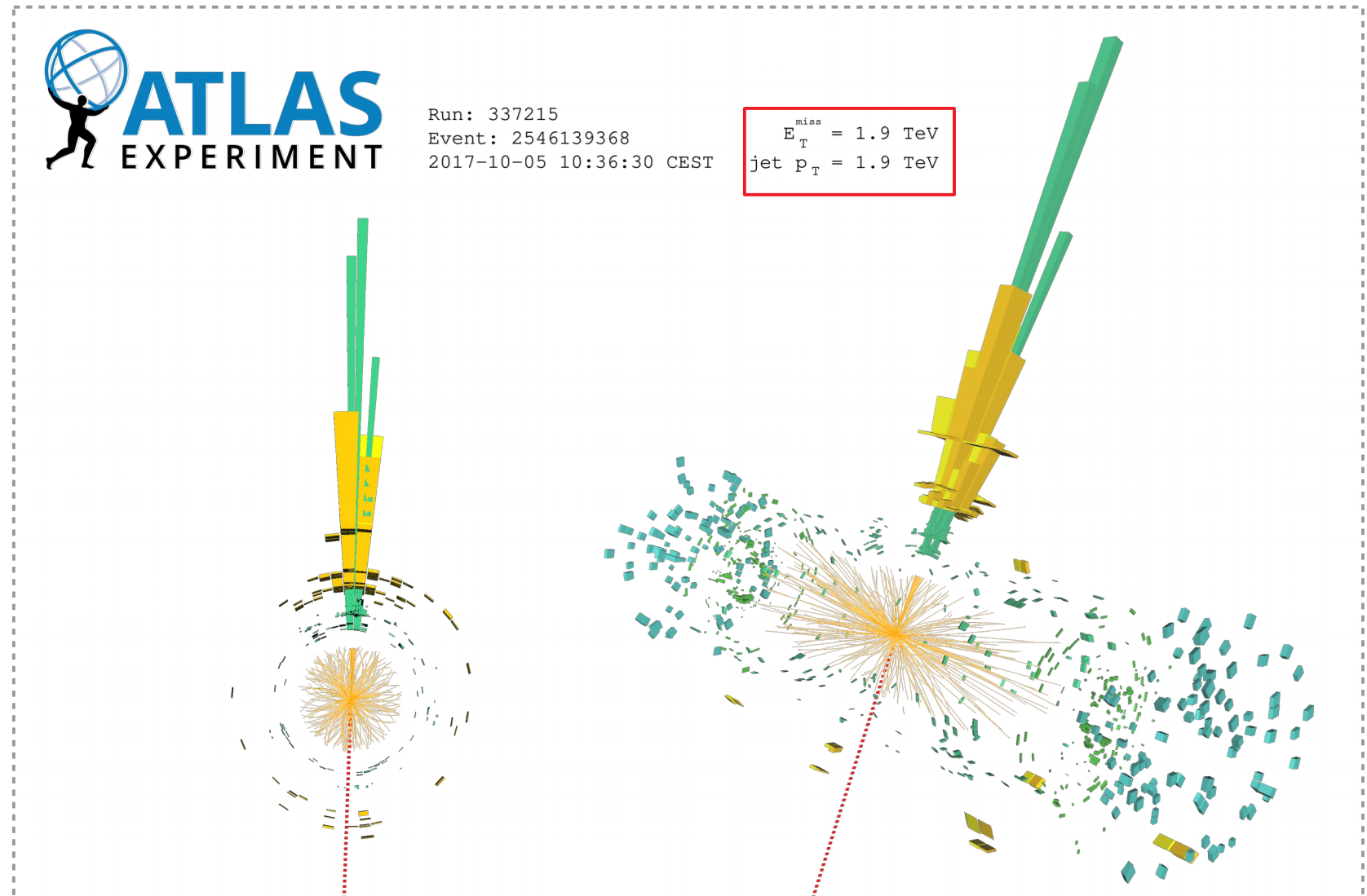
MET+jet

MET+photon

MET+W/Z

A classic DM candidate event

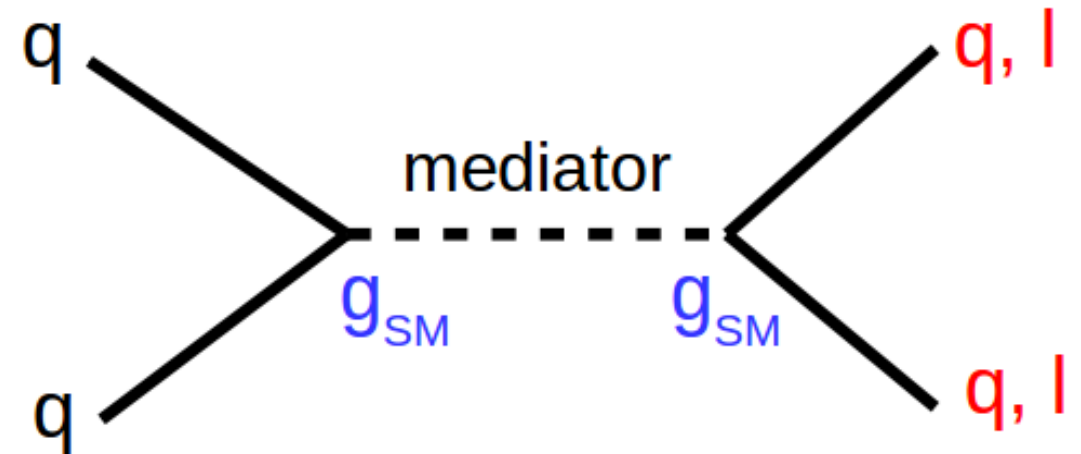
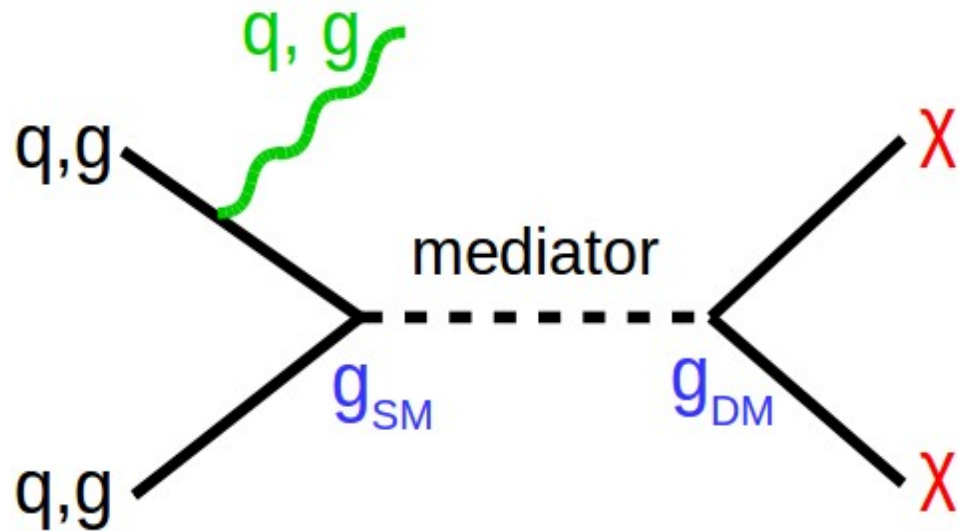
- > MET+jet signature
- > ATLAS, 2017



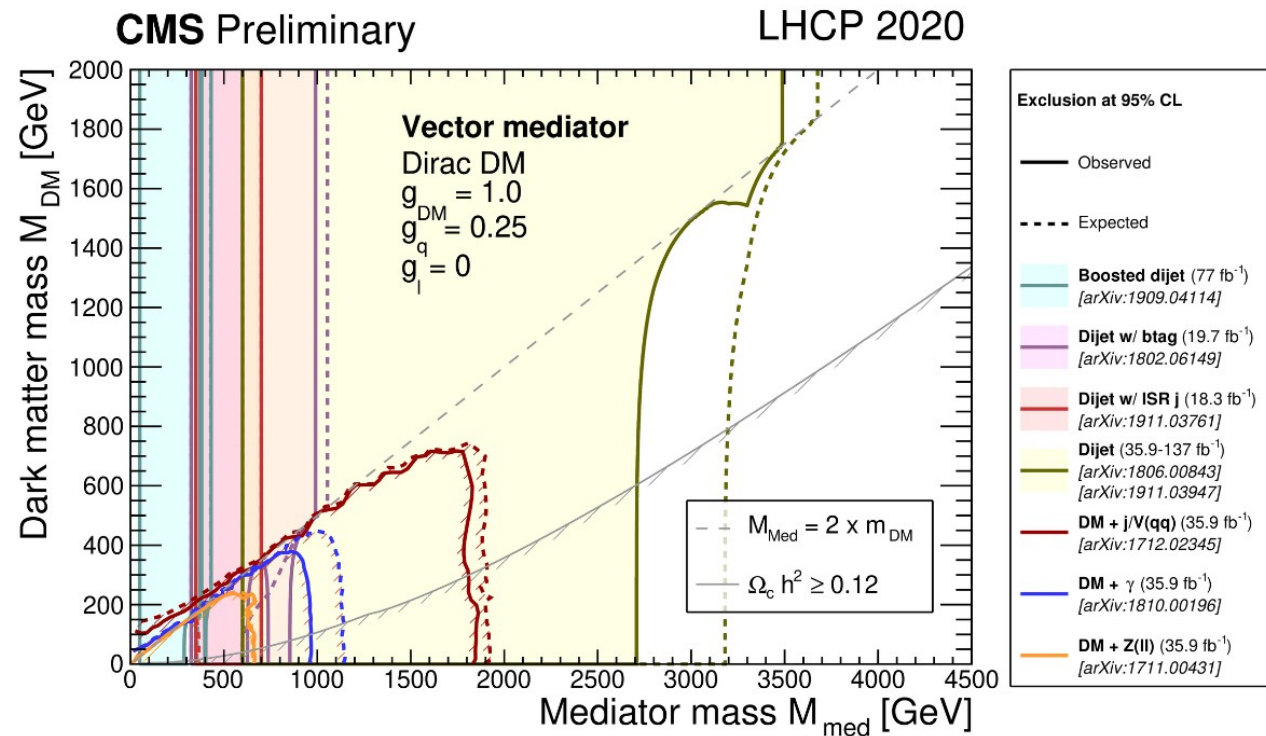
s-channel mediators

- > Mediators can decay back into (visible) SM fermions → [resonance searches](#)!

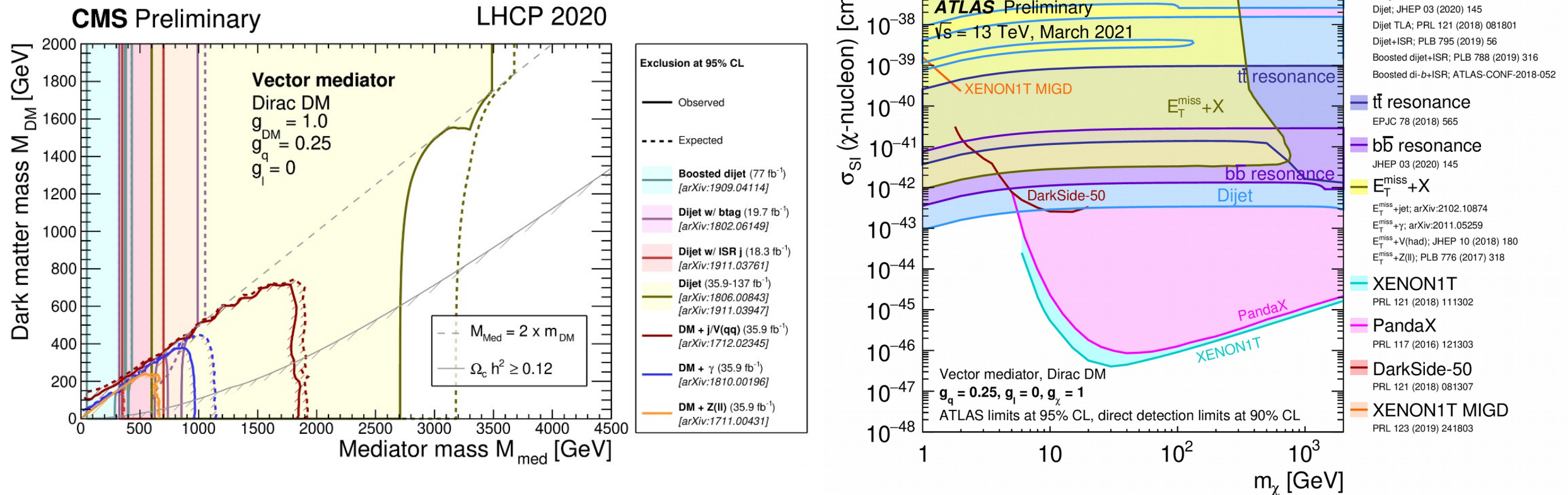
Two complementary search strategies at the LHC!



- > Various resonance searches ([visible decays](#)) probe mediator mass range from 50 GeV to above 3 TeV
- > MET+jet search gives best sensitivity among MET+X searches ([invisible decays](#))

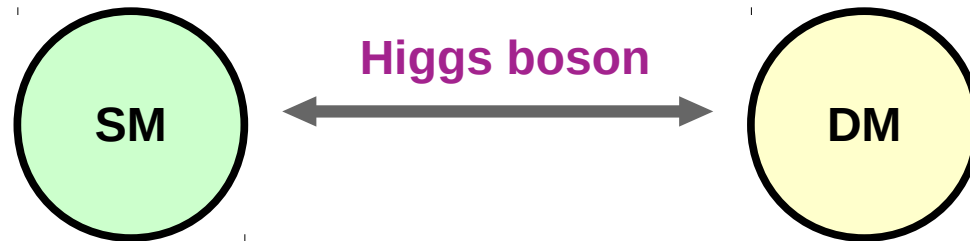


- > Various resonance searches (**visible decays**) probe mediator mass range from 50 GeV to above 3 TeV
- > MET+jet search gives best sensitivity among MET+X searches (**invisible decays**)
- > Comparison with **direct detection** results → **collider sensitivities very model dependent!**

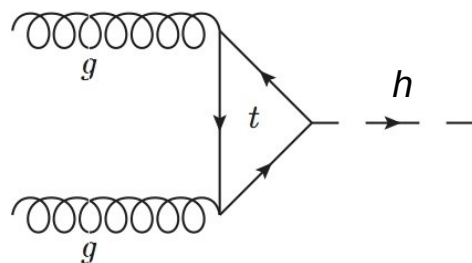


B. Higgs portal models

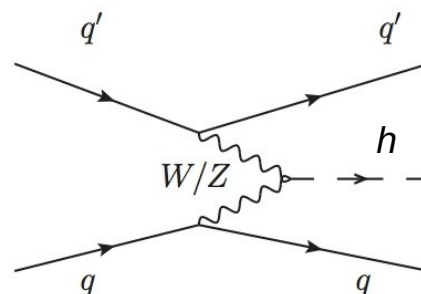
- > Higgs boson as mediator between SM and DM
- > Invisible Higgs boson decays to dark matter increase $\text{BR}(h \rightarrow \text{inv})$ compared to SM prediction
 - **SM:** $\text{BR}(h \rightarrow \text{inv}) = 0.1\%$ from $h \rightarrow ZZ^* \rightarrow 4\nu$



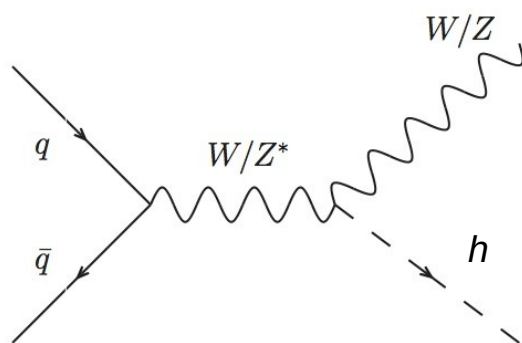
- > Focus on production modes with additional visible particles in the final state



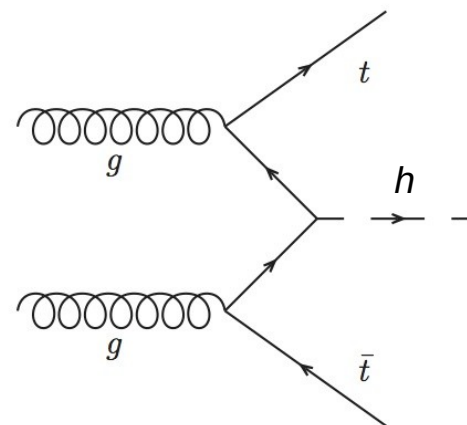
Gluon fusion



Vector-boson fusion (VBF)



Higgs strahlung (Vh)

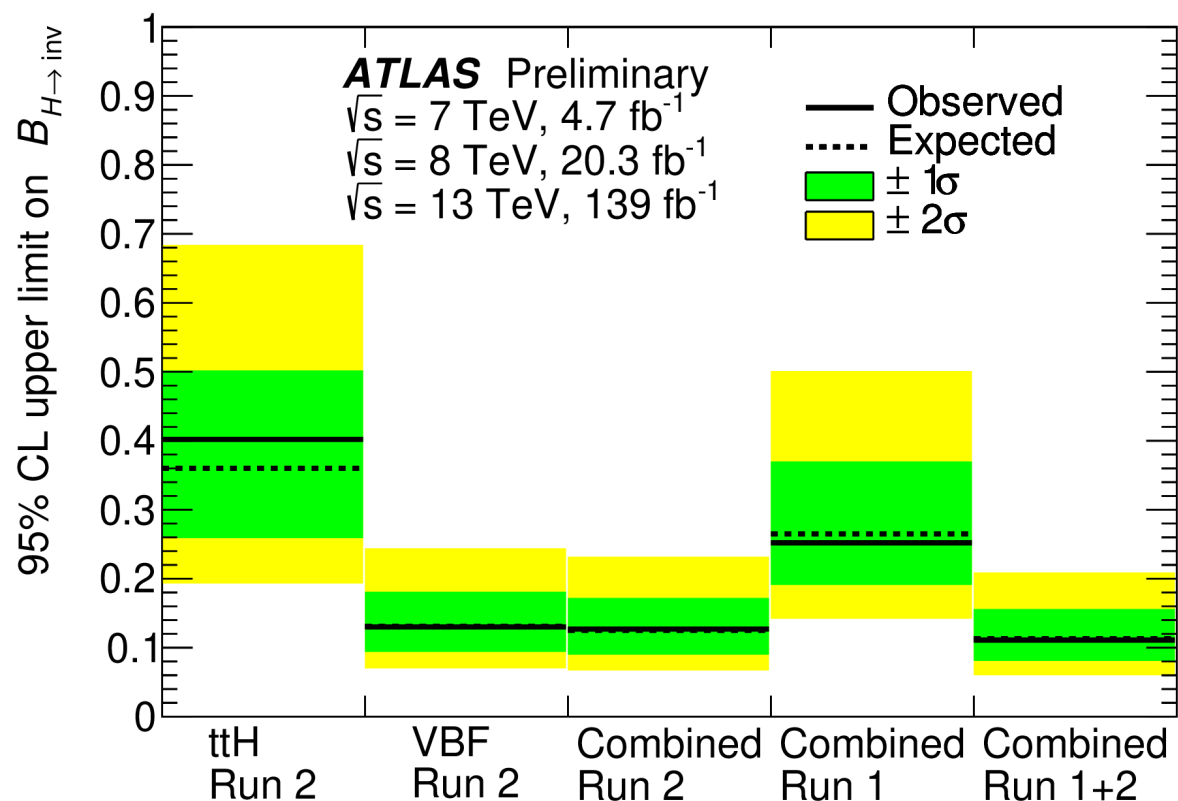


Top-quark associated (tth)

Combination of $h \rightarrow \text{inv}$ searches

ATLAS: ATLAS-CONF-2020-052
CMS: PLB 793 (2019) 520

- > Includes Run 2 results targeting Higgs production from **VBF** and **ttH** (0L and 2L channels)
- > **Statistical combination** with additional results obtained at $\sqrt{s} = 7$ and 8 TeV
- > **Preliminary**: final Run 2 combo will include more, e.g. MET+Z(ll) [ATLAS-CONF-2021-029], VBF+ γ +MET [ATLAS-CONF-2021-004]

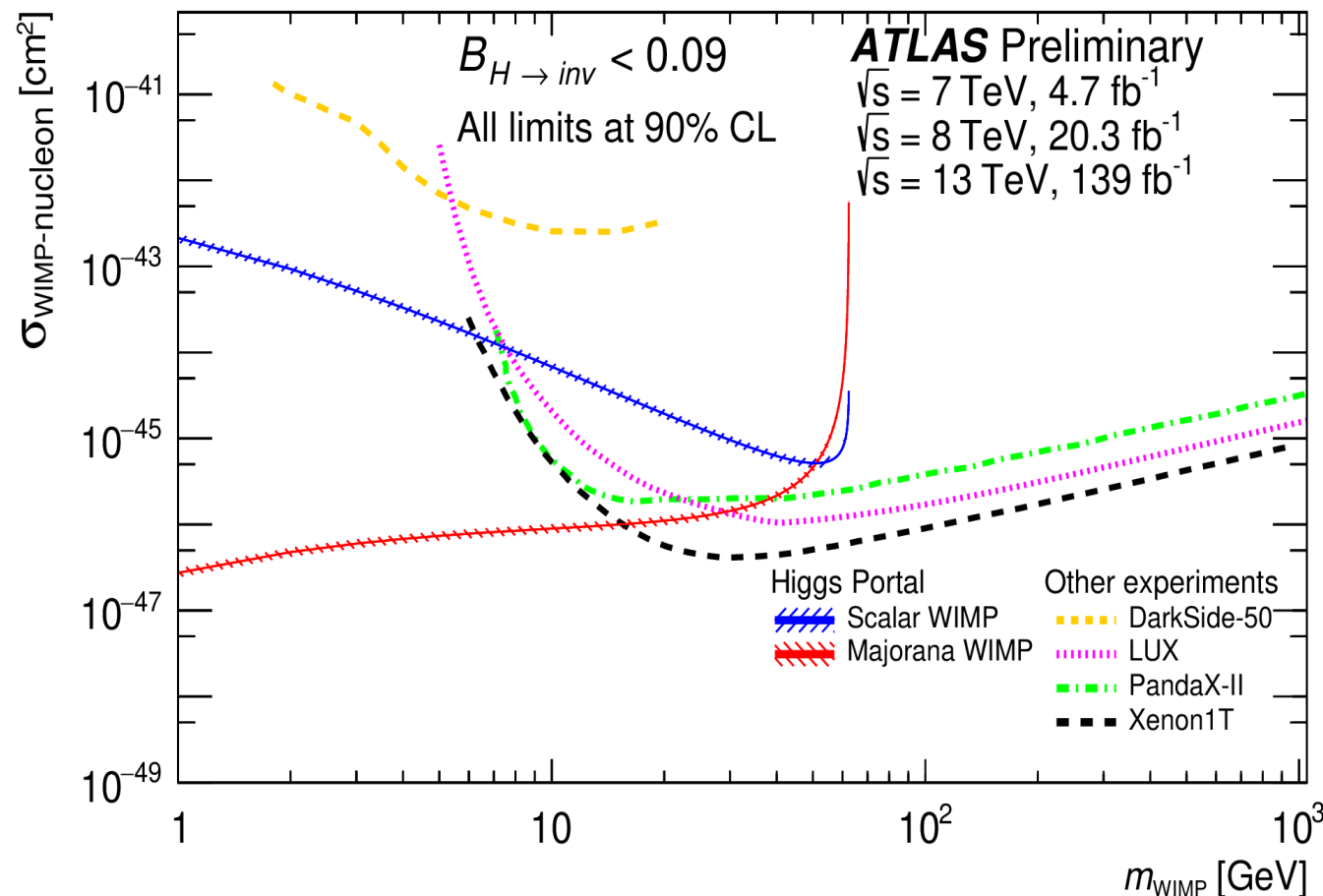


$BR(h \rightarrow \text{inv}) < 0.11$ ($0.11^{+0.04}_{-0.03}$)
at 95% CL

Latest CMS combination
based on 35 ifb:

$BR(h \rightarrow \text{inv}) < 0.19$ (0.15)
at 95% CL

- > Includes Run 2 results targeting Higgs production from **VBF** and **tth** (0L and 2L channels)
- > **Statistical combination** with additional results obtained at $\sqrt{s} = 7$ and 8 TeV
- > **Preliminary**: final Run 2 combo will include more, e.g. MET+Z(l) [ATLAS-CONF-2021-029], VBF+ γ +MET [ATLAS-CONF-2021-004]

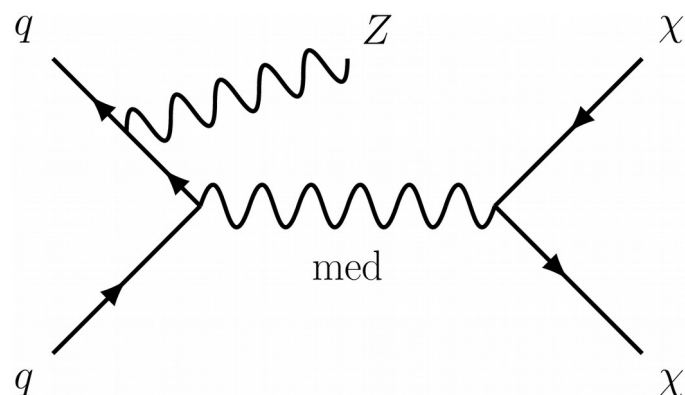


Complementary sensitivity to direct-detection experiments for both **scalar** and **Majorana** WIMPs at low masses

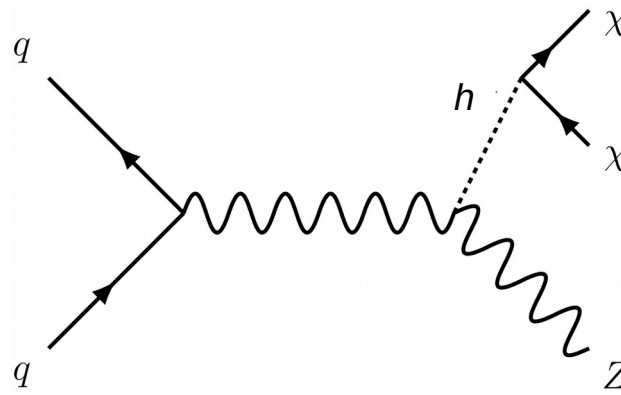
- > Single analysis provides sensitivity to a range of beyond-SM processes (not only DM)
- > Targeting decays to ee or $\mu\mu$
- > Main backgrounds: ZZ, WZ, Z+jets, non-resonant backgrounds (W+jets, $t\bar{t}$, ...)
 - Dedicated control regions to obtain normalisations for most backgrounds
 - Combined fit to signal and control regions



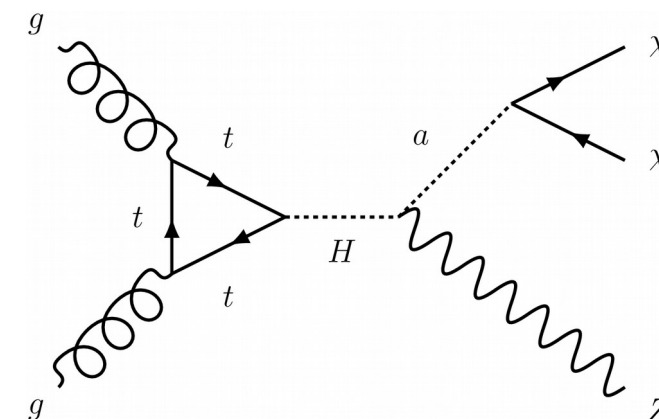
Simplified s-channel
mediator model



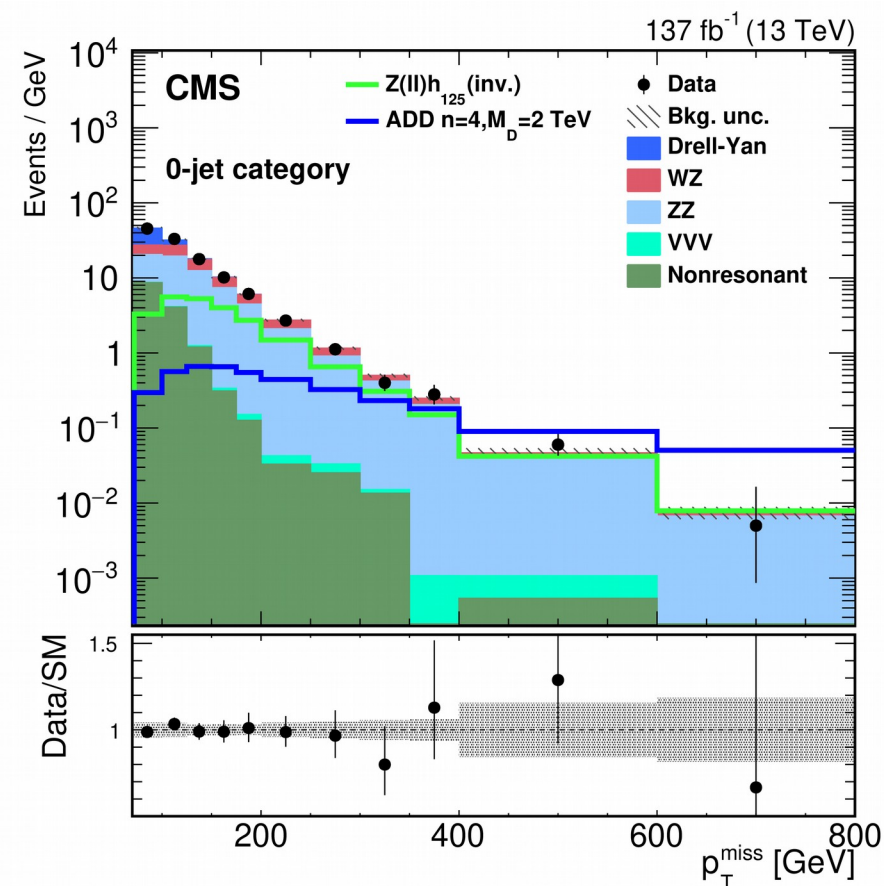
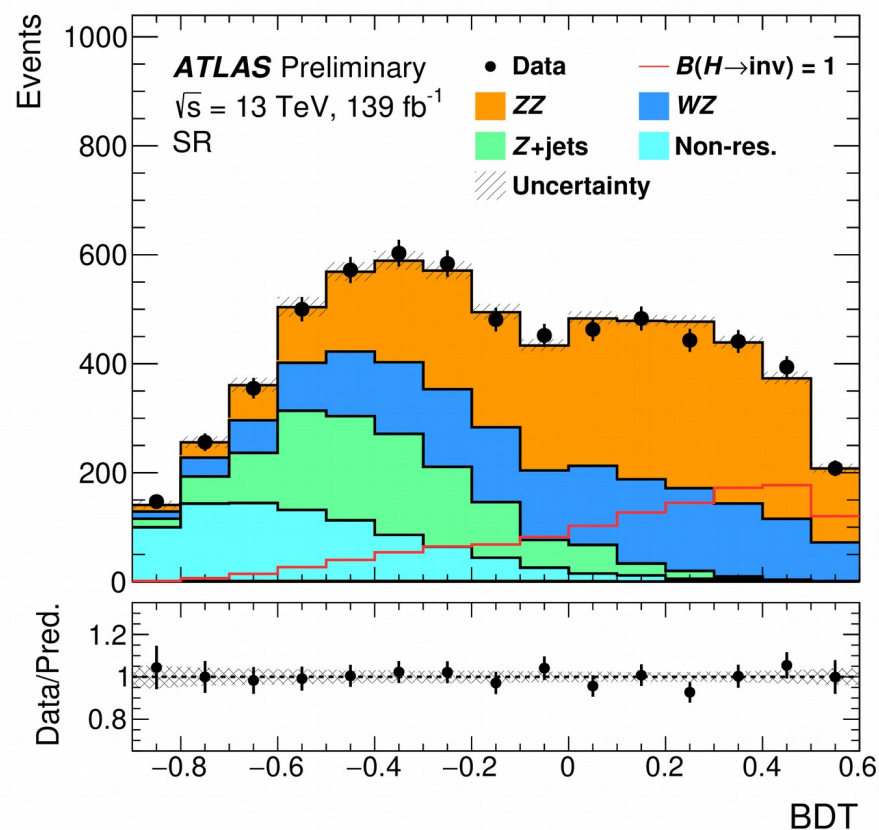
Higgs portal model
(associated ZH production)



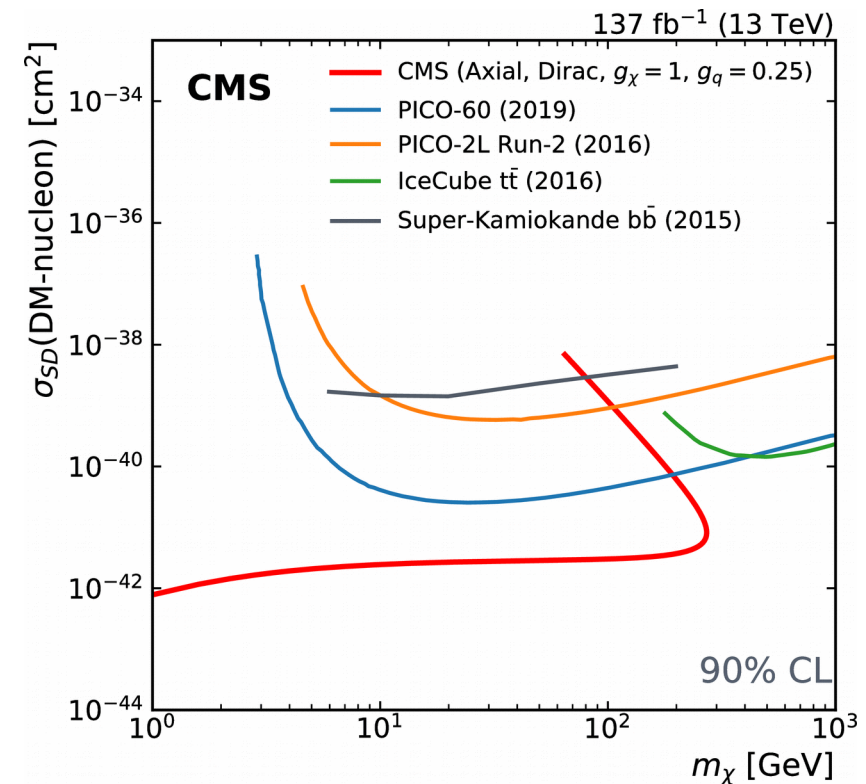
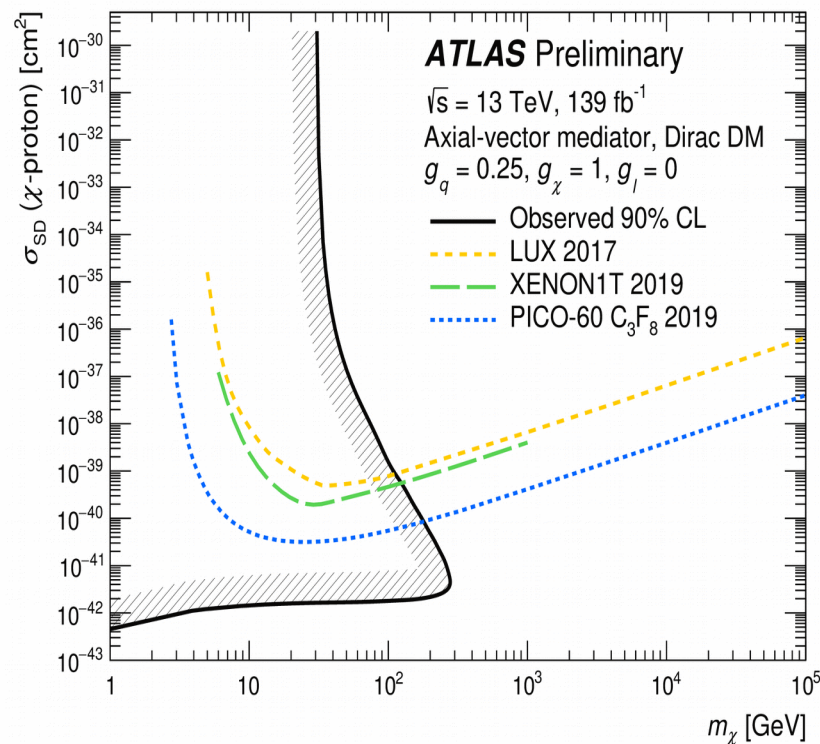
2HDM+a
(resonant production)



- > Different sensitive variables depending on target signature
 - **BDT output** (ATLAS: $h \rightarrow \text{inv}$); **MET** (CMS: $h \rightarrow \text{inv}$, simp. models); **transverse mass** (2HDM+a)
- > CMS further splits signal region in 0- and 1-jet categories to improve sensitivity

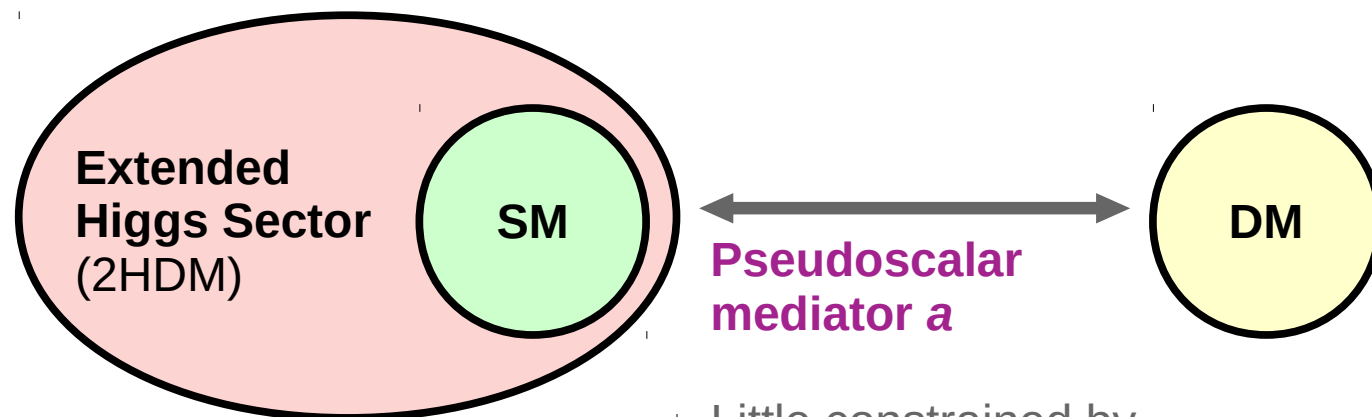


- > Upper limit on Higgs-to-invisible decays:
 - **ATLAS:** $BR(h \rightarrow inv) < 0.18$ (0.18) at 95% CL
 - **CMS:** $BR(h \rightarrow inv) < 0.29$ (0.25) at 95% CL
- > Complementary constraints to direct detection for (axial-)vector simplified model



C. Less simplified model: 2HDM+a

- > Embed SM in more complete theory, e.g. involving 2HDM
- > **More complete theory**, more diverse range of possible signatures



- Scalars: h, H ,
- Pseudoscalar: A ,
- Charged Higgs: $H^\pm$

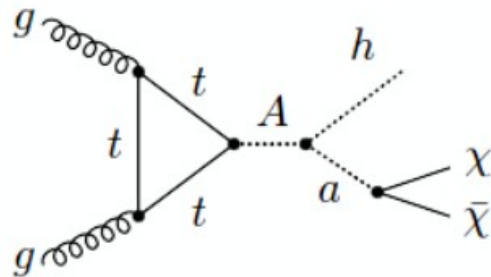
Little constrained by
direct detection
experiments

LHC Dark Matter Working Group:
Phys. Dark Univ. 27 (2020) 100351

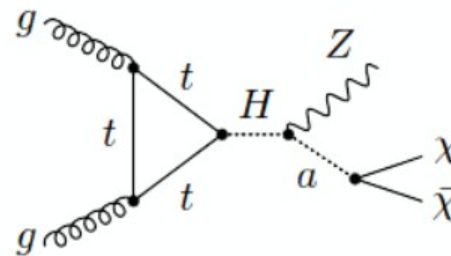
Bauer, Haisch, Kahlhoefer:
JHEP05(2017) 138

C. 2HDM+a

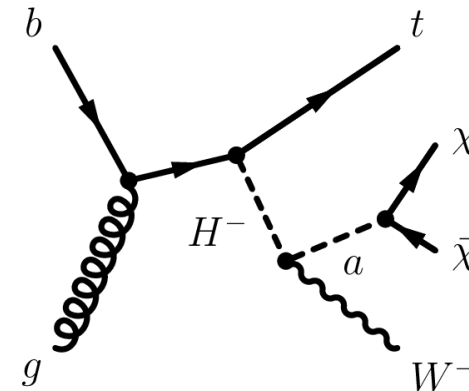
- > Variety of signatures with both visible and invisible decays
 - Resonantly enhanced production of MET+h and MET+Z signatures
 - Processes not predicted by simplified models
 - Inspires new searches, e.g. MET+tW search (ATLAS: CERN-EP-2020-184, see backup slides)



MET+h



MET+Z

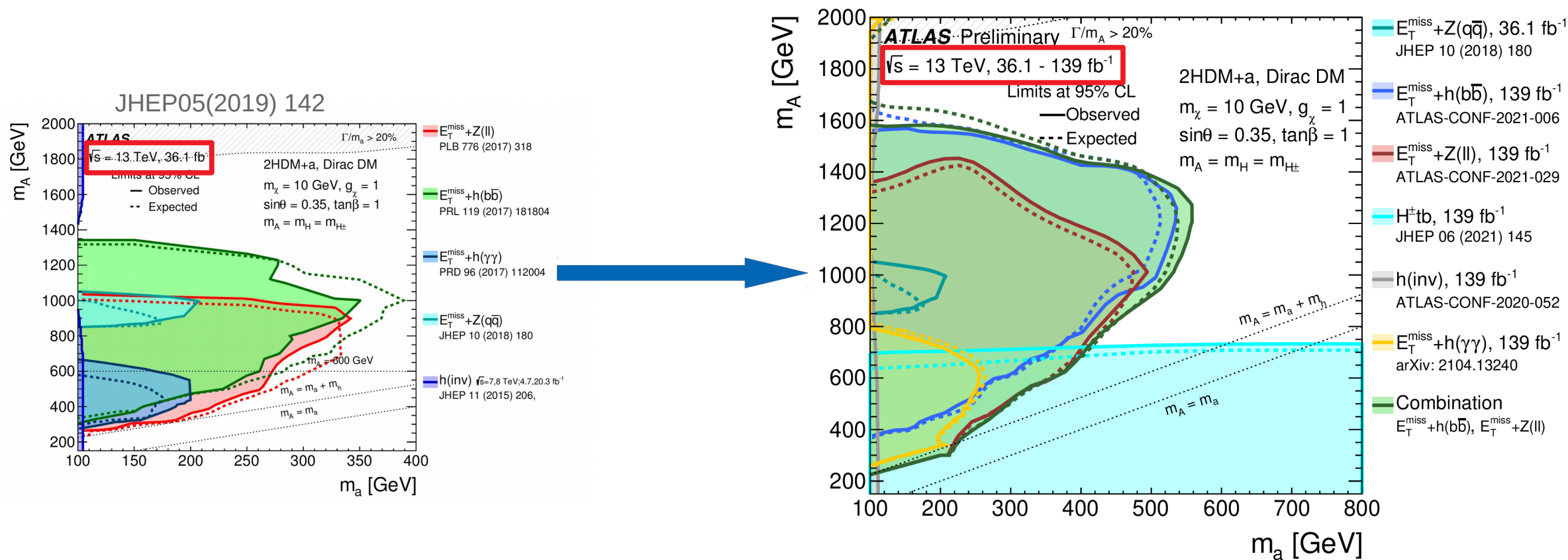


MET+tW

Summary of constraints on the 2HDM+a

ATLAS: ATLAS-CONF-2021-036

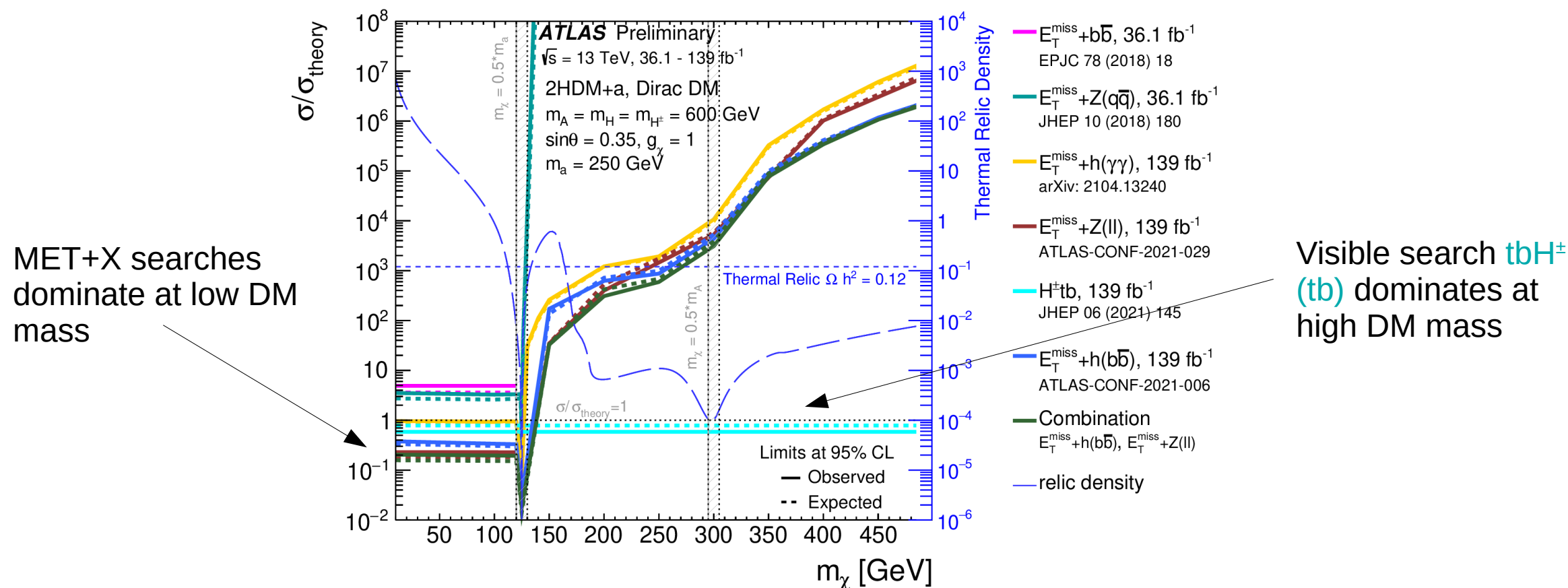
- > Various updates compared to summary paper on *partial* Run-2 dataset [JHEP05(2019) 142]
 - Addition of new signatures: $tbH^\pm(tb)$ [link] and MET+tW [link]
 - Statistical combination of the two most sensitive searches: MET+h(bb) [link] and MET+Z(ll) [link]



Summary of constraints on the 2HDM+a

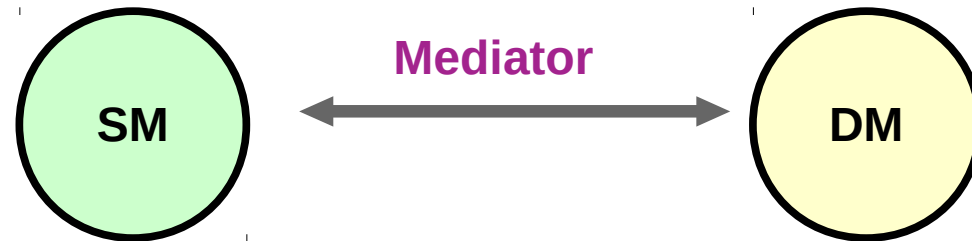
ATLAS: ATLAS-CONF-2021-036

- > Various updates compared to summary paper on *partial* Run-2 dataset [JHEP05(2019) 142]
 - Addition of new signatures: $tbH^\pm(tb)$ [link] and MET+tW [link]
 - Statistical combination of the two most sensitive searches: MET+h($b\bar{b}$) [link] and MET+Z(ll) [link]



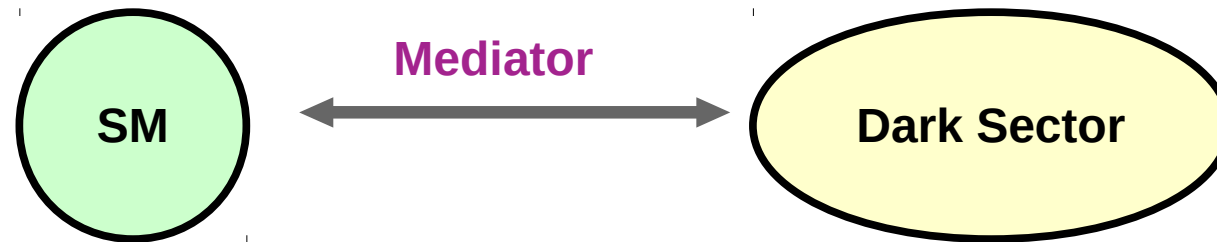
D. Extended dark sector models

- > Assume there is more than one type of DM particle



D. Extended dark sector models

- > Assume there is more than one type of DM particle

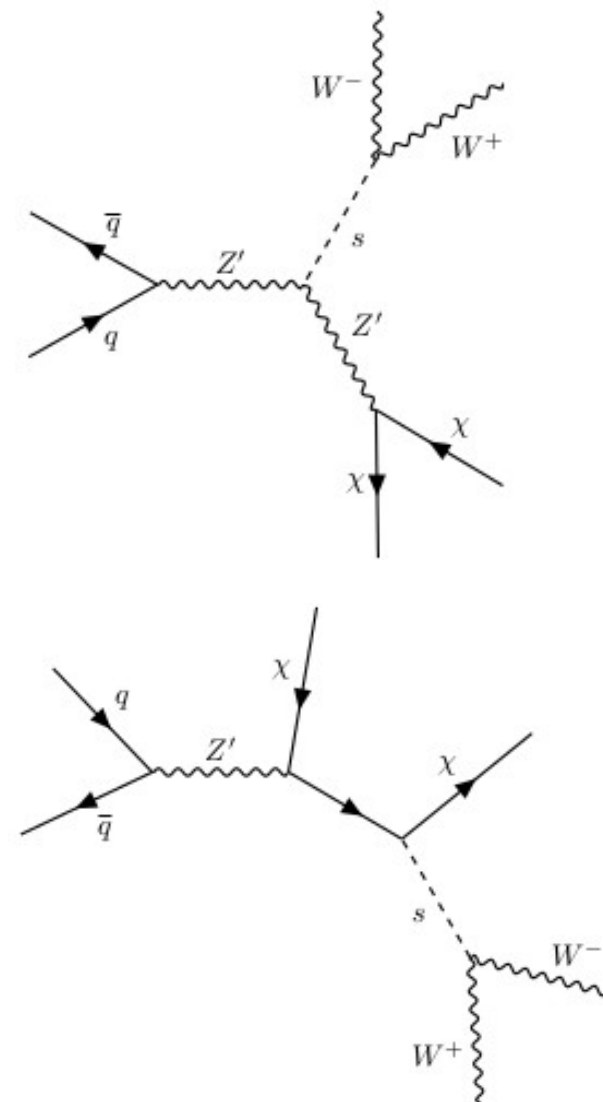


Disclaimer:

Various interesting signatures predicted in dark sector models, including long-lived particles (see talks by [M.Verducci](#) and [M.Kazana](#))

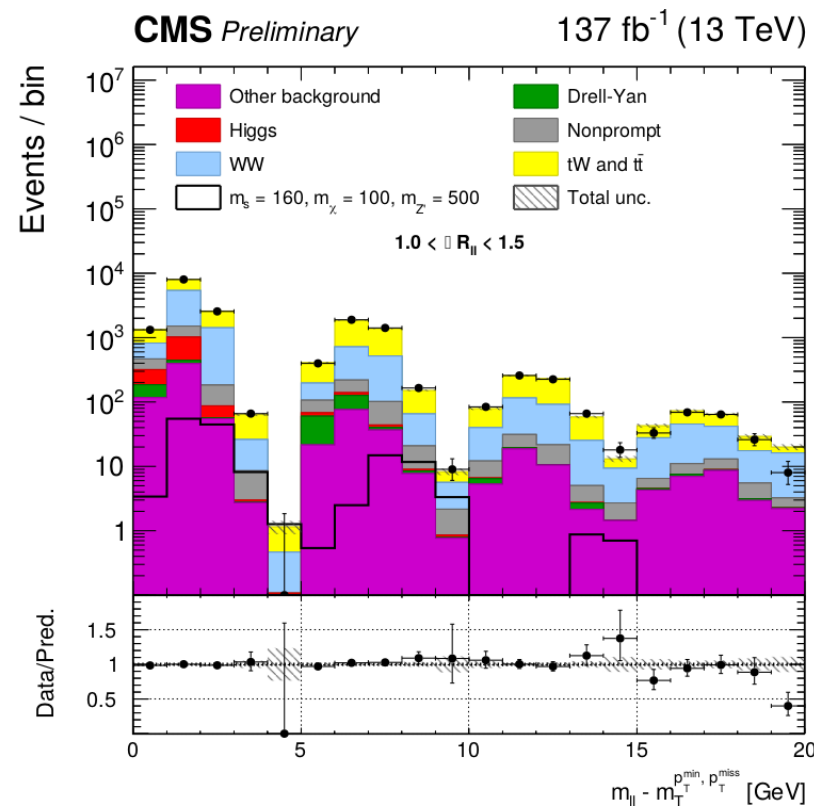
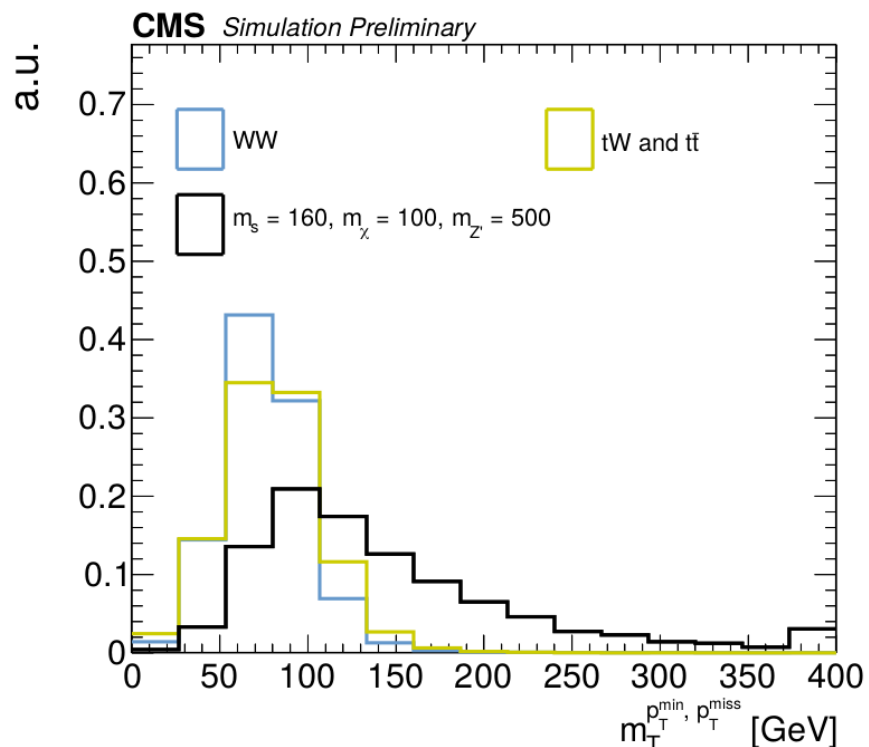
Only one example shown here

- > Assume DM particles acquire mass through their interaction with a **dark Higgs boson**
- > Dominant Dark Higgs decay modes:
 - bb for $m_s < 160$ GeV
 - WW for $m_s > 160$ GeV
- > ATLAS and CMS searches targeting the WW final state
 - ATLAS: $WW \rightarrow$ allhadronic
 - CMS: $WW \rightarrow$ 2-lepton



> **CMS:** 2 opposite signed isolated leptons with large MET

- Major backgrounds:
 - Non-prompt leptons: data-driven (tight to loose method)
 - WW, ttbar, Z $\rightarrow\tau\tau$ rate: shape from simulation, normalisation from CR
- 3D fit in ΔR_{ll} , m_{ll} and m_T

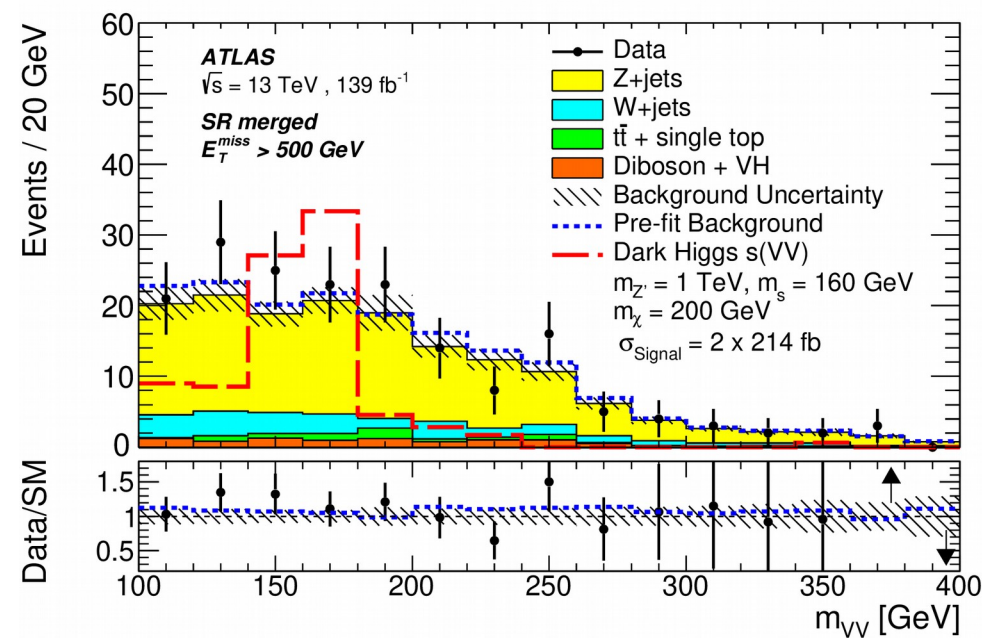
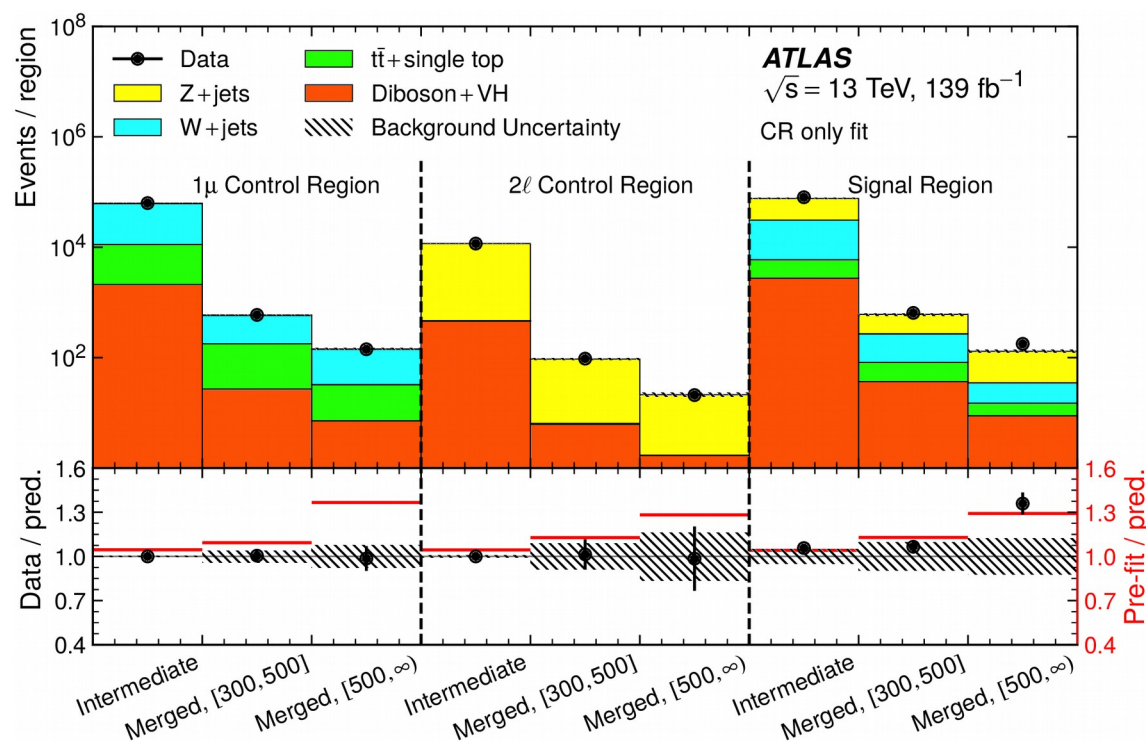
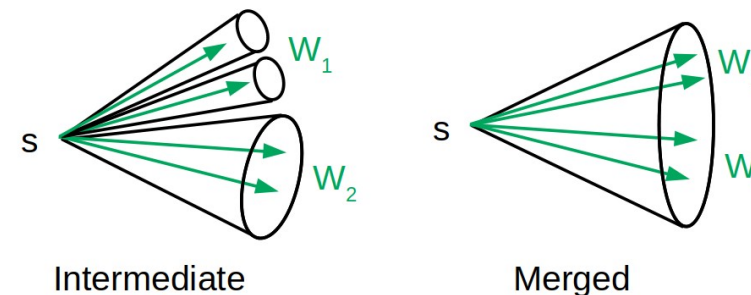


Searches for Dark Higgs bosons

ATLAS: PRL 126 (2021) 121802
CMS: CMS-PAS-EXO-20-013

> ATLAS: 2 hadronically decaying W bosons with large MET

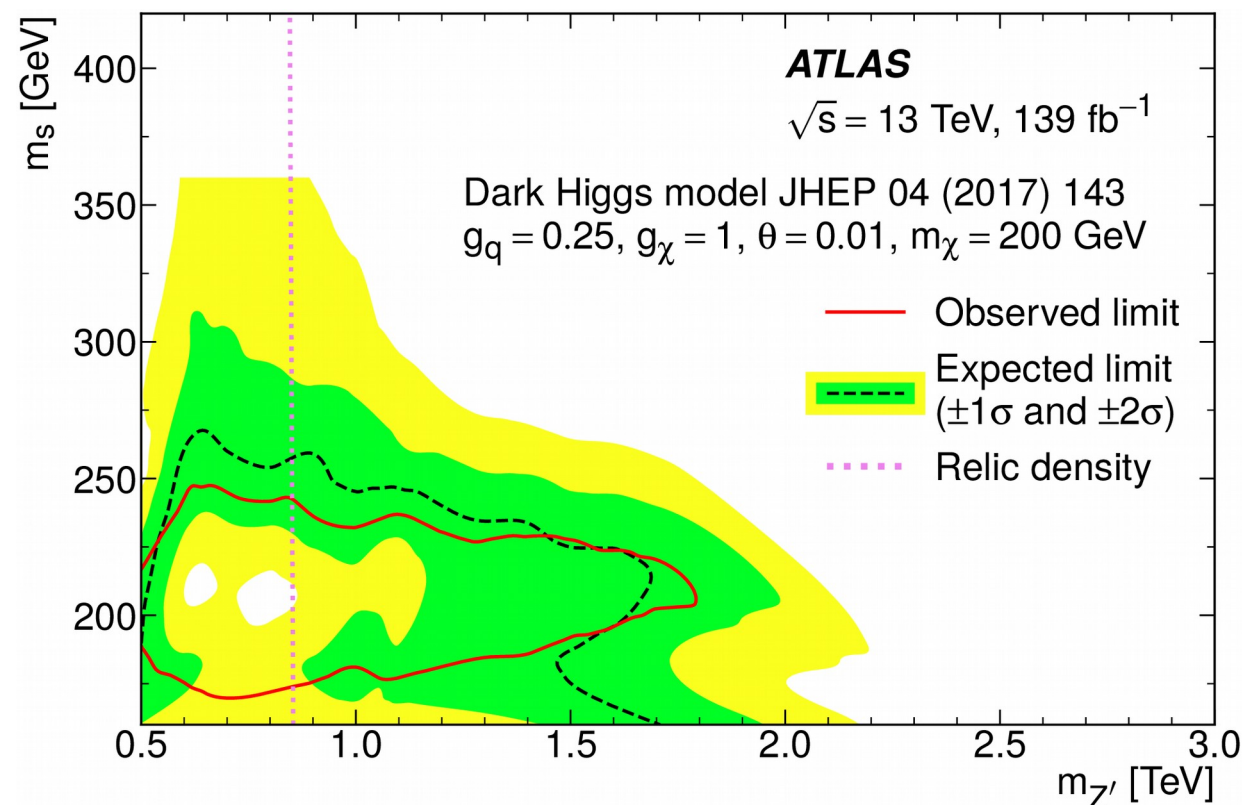
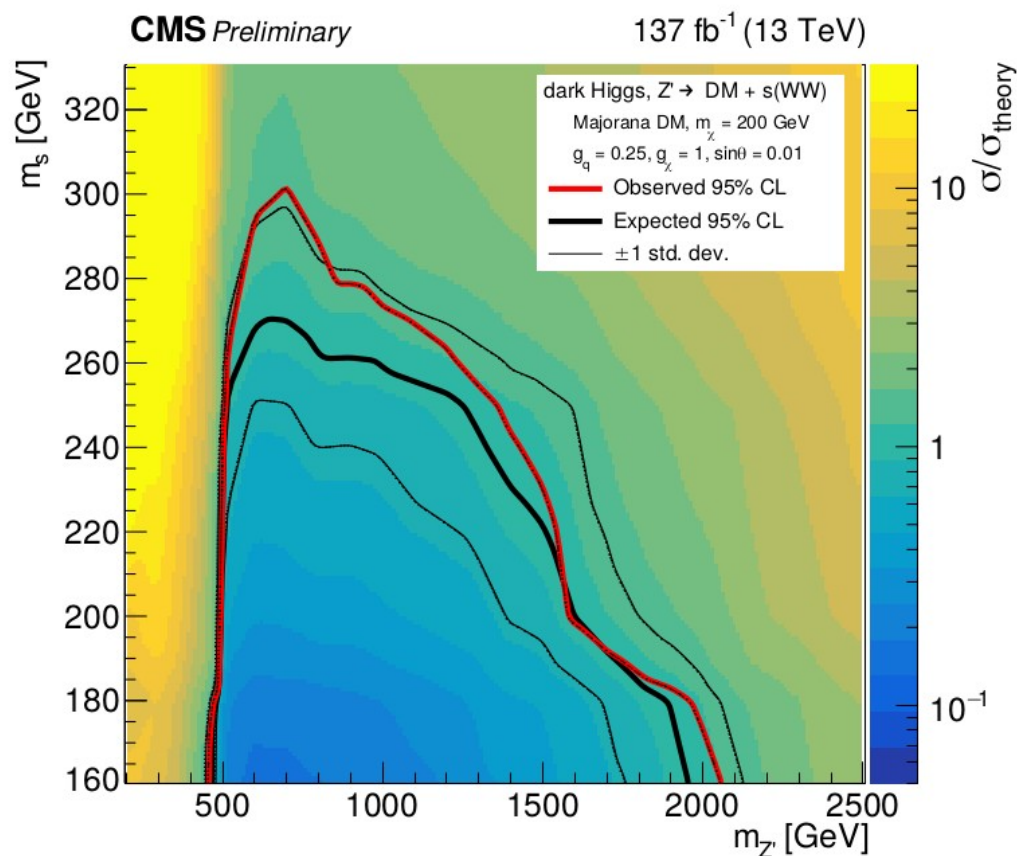
- Major backgrounds: V+jets
 - Estimated from single-muon and 2L control regions
- Merged Dark Higgs decays reconstructed from large-R jets
 - Substructure calculated from track-based quantities for better resolution [ATL-PHYS-PUB-2018-012]



Searches for Dark Higgs bosons

ATLAS: PRL 126 (2021) 121802
CMS: CMS-PAS-EXO-20-013

- > No excess observed in either ATLAS or CMS
- > Exclusion limits can be compared within common benchmark
 - Expected sensitivities comparable



Conclusion and Outlook

> Rich programme of DM searches in ATLAS and CMS

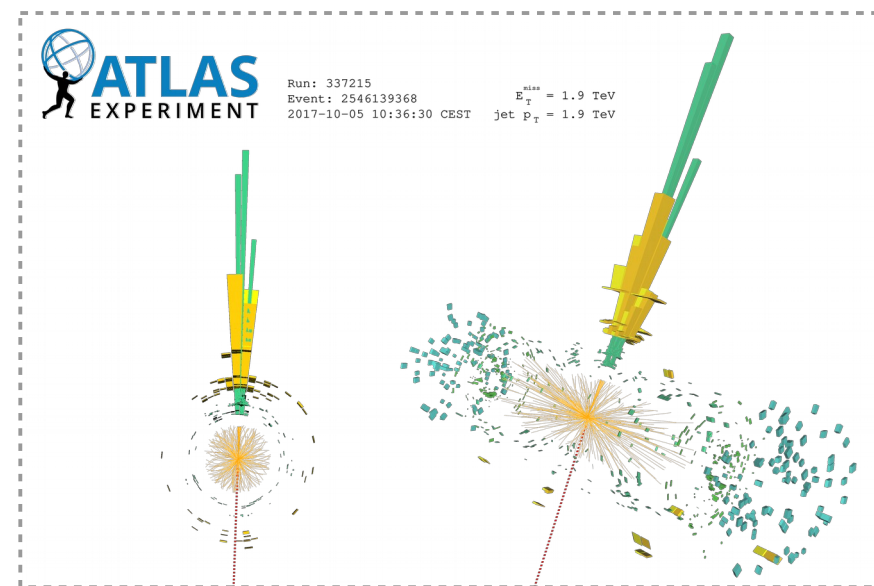
- Complementary sensitivities from searches targeting visible or partially invisible final states
- Sensitivity from searches not specifically targeting DM

> Fruitful interplay between theory and experiment (e.g. via LHC DM Working Group)

- Benchmark models to compare results from different experiments
- Models inspire of new searches

> Many new results from searches using the full Run-2 dataset

- No significant excess discovered so far...
- ... but many searches are still in progress



Thank you for your attention!



Contact: **Dr. Katharina Behr** (katharina.behr@desy.de)

Helmholtz Young Investigator Group Leader

https://atlas.desy.de/external_grants/katharina_behr_yig/

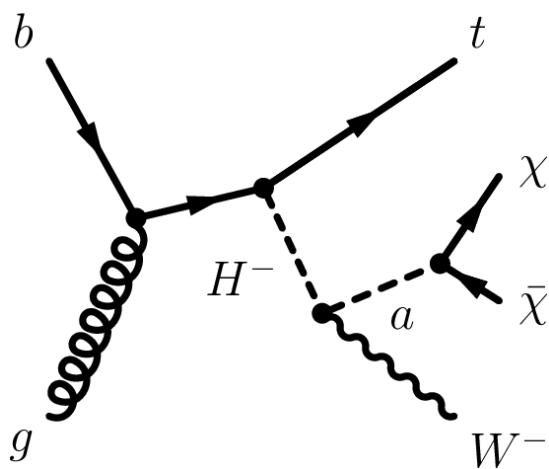
Extra Material



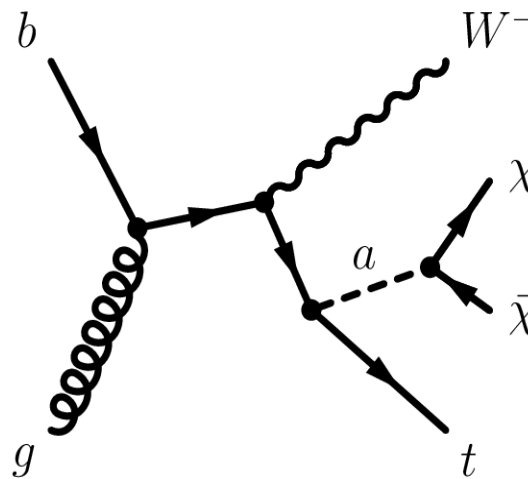
A new top-dark-matter signature at the LHC

- > Predicts new single-top signatures: tW +MET and tj +MET (previously largely unprobed)

Representative diagrams for tW +MET signature



Not in simplified model

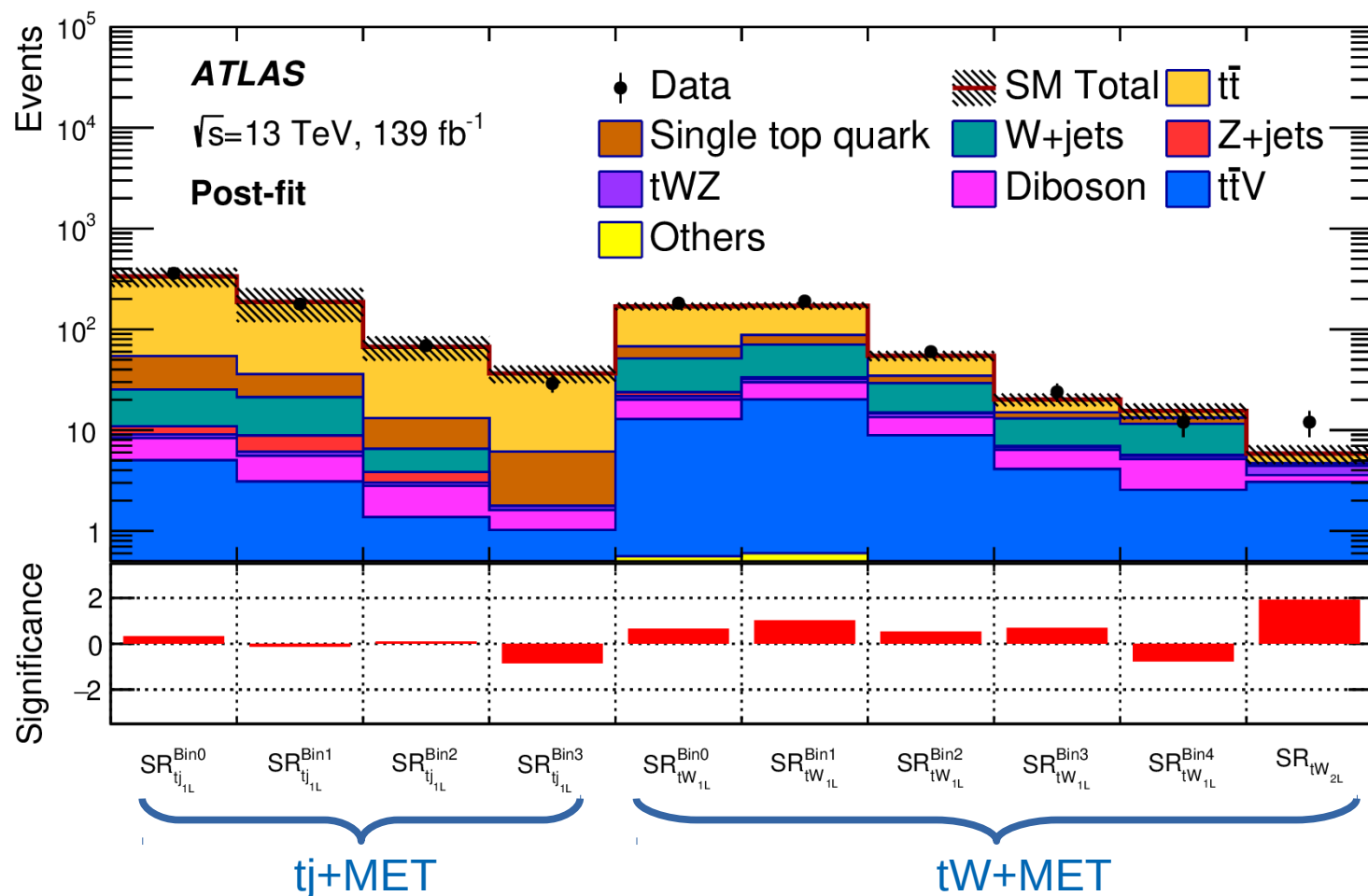


Predicted also by simplified model

Pani, Polesello:
Phys. Dark Univ.21(2018) 8-15

A new search for dark matter with tops

- > 10 different signal regions based on lepton multiplicity and other discriminating variables
- > Good agreement with SM, largest excess ($< 2\sigma$) in tW_{2L} region

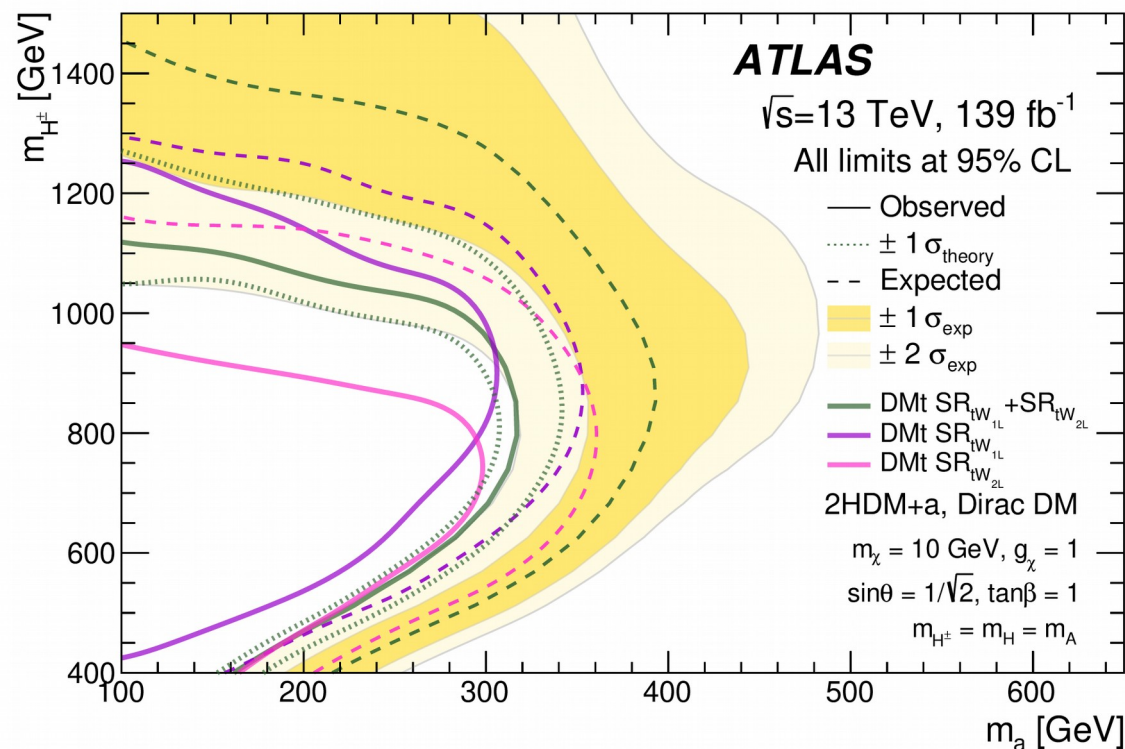


A new search for dark matter with tops

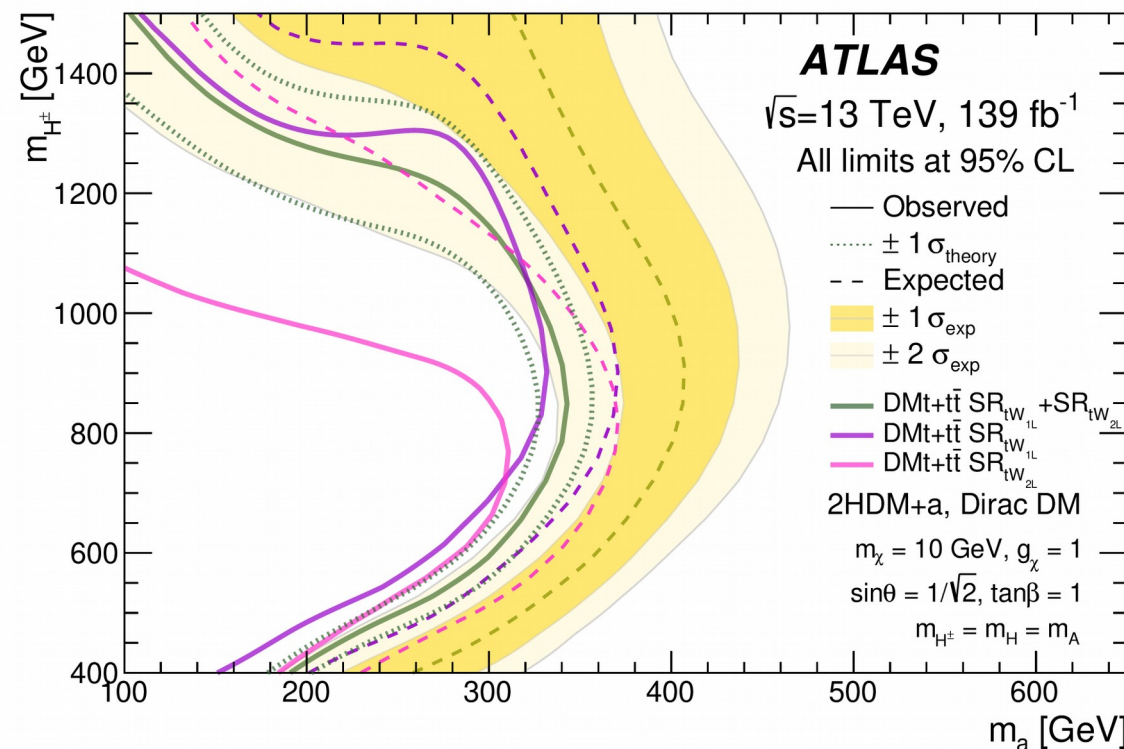
ATLAS: CERN-EP-2020-184

Accepted by Eur. Phys. J. C

> Exclusion contours from the tW +MET search in the 2HDM+a benchmark



Only tW +MET results

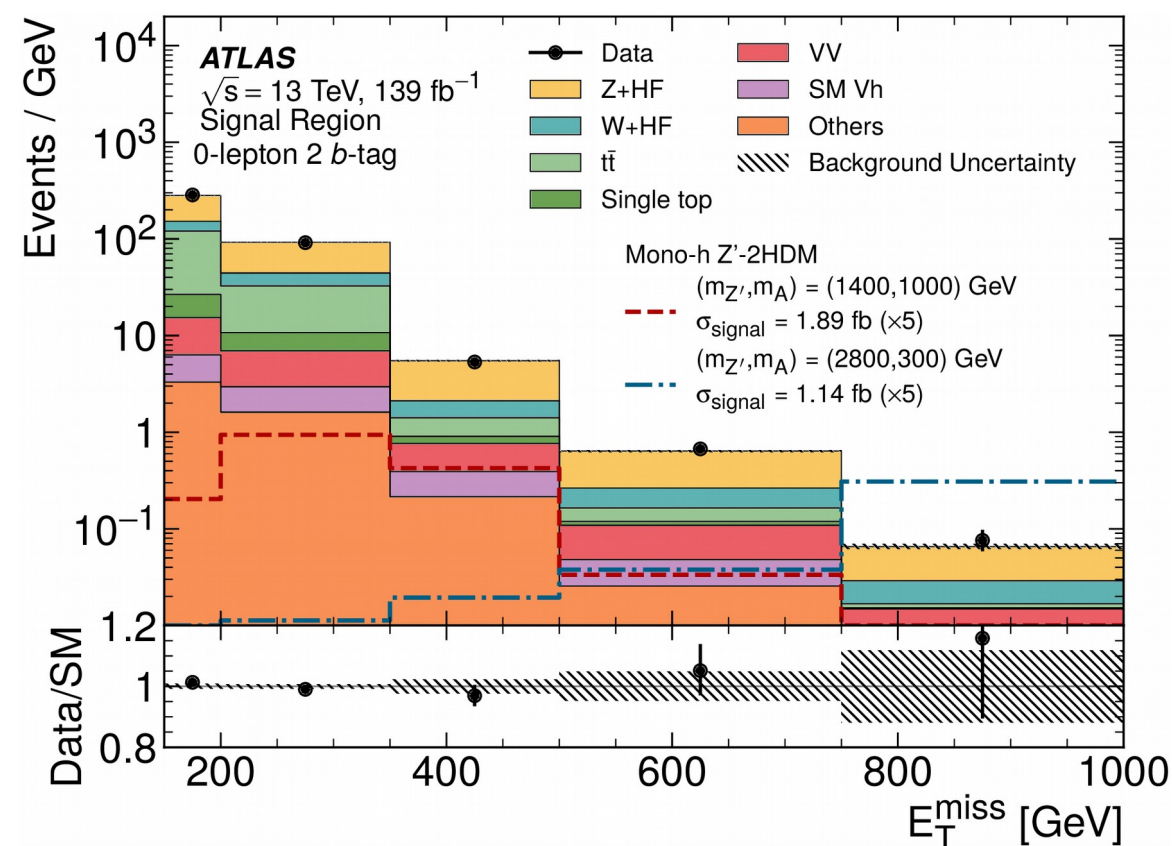
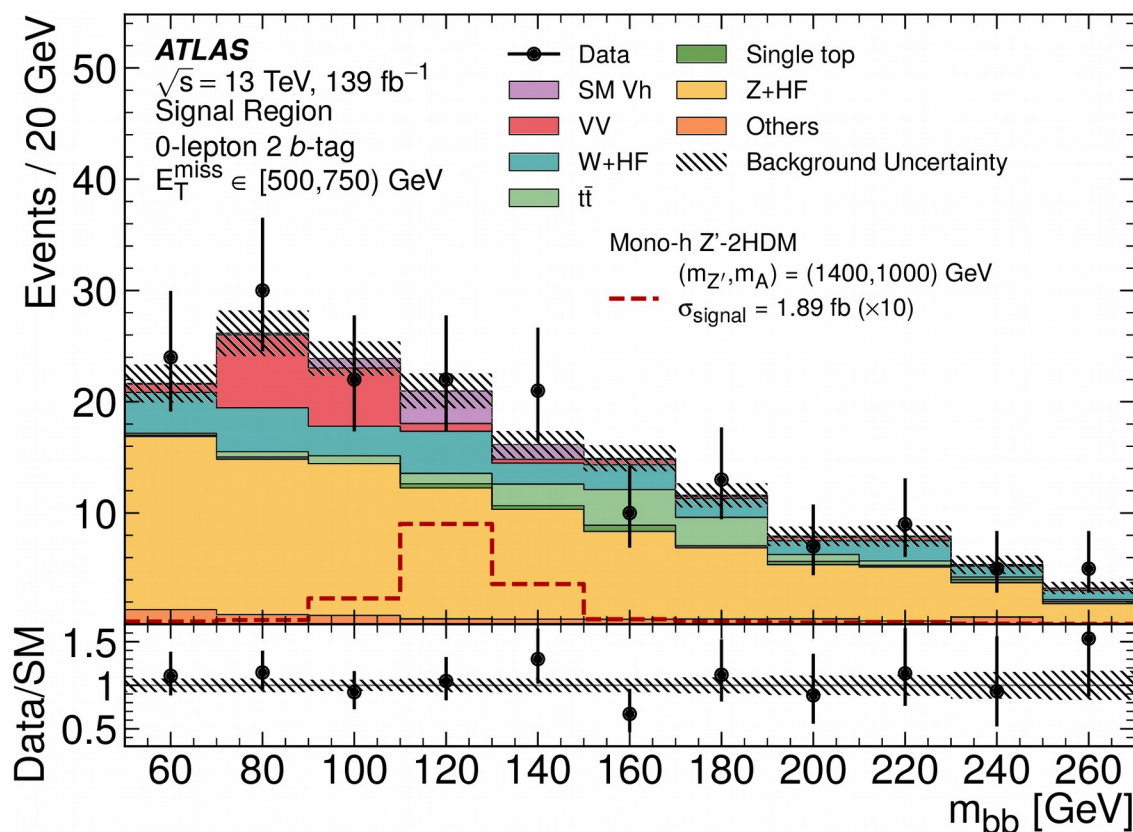
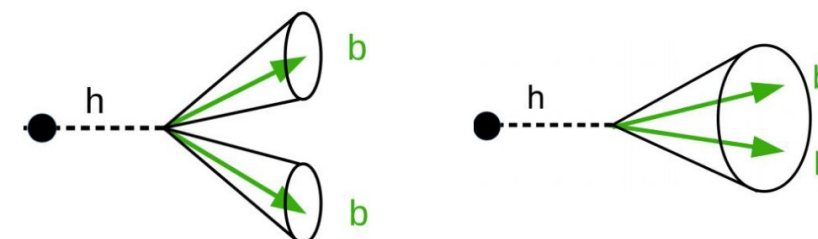


Combined tW +MET and $t\bar{t}$ +MET results

Search for MET+h(bb)

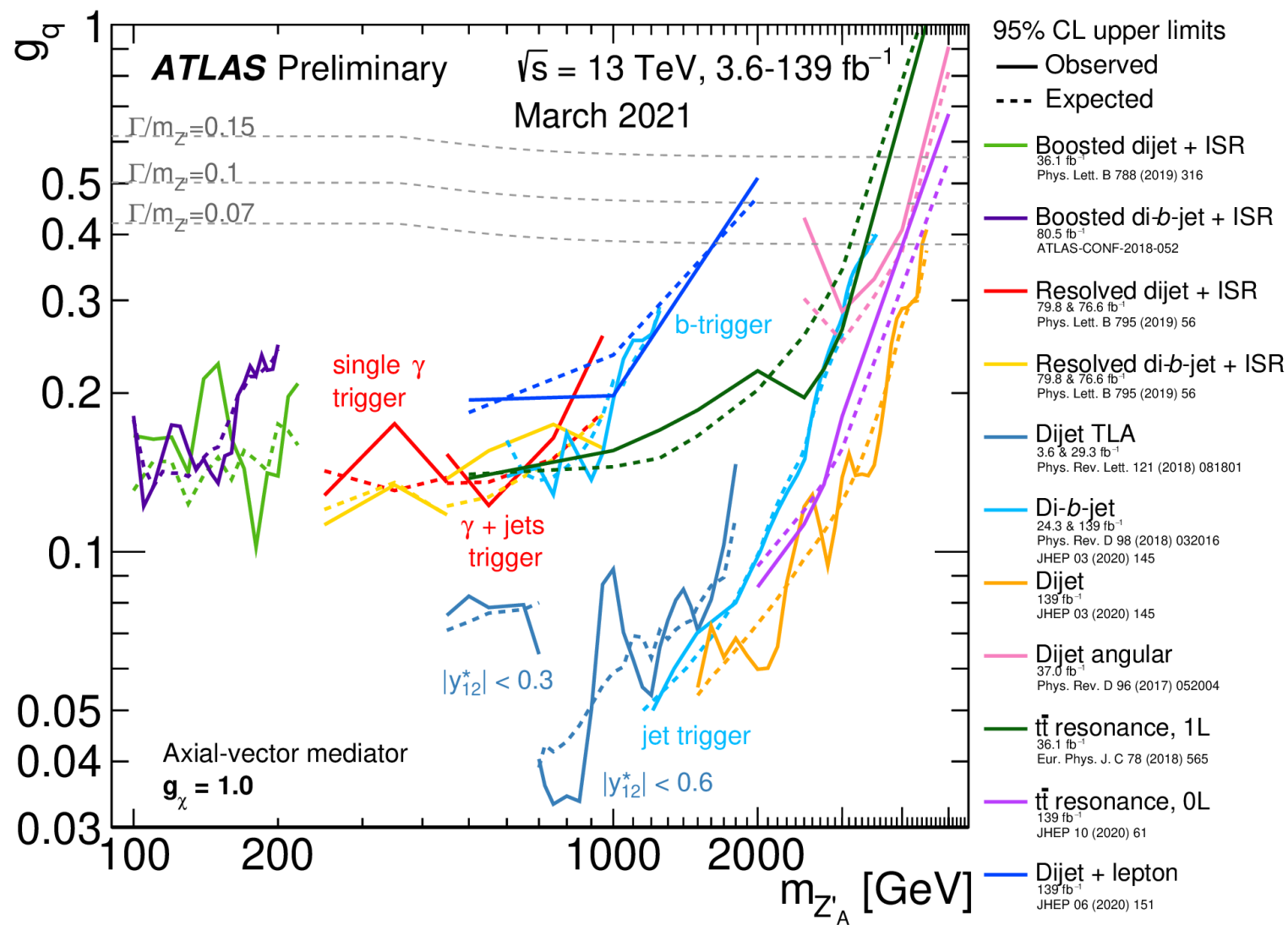
ATLAS: [arxiv:2108.13391](https://arxiv.org/abs/2108.13391)

- > Sensitive to a range of DM processes, e.g. in 2HDM+a, 2HDM+Z'
- > Targets **both resolved and merged topologies** of $h \rightarrow bb$ decays
- > Simultaneous fit to the Higgs mass distributions in SR and CRs



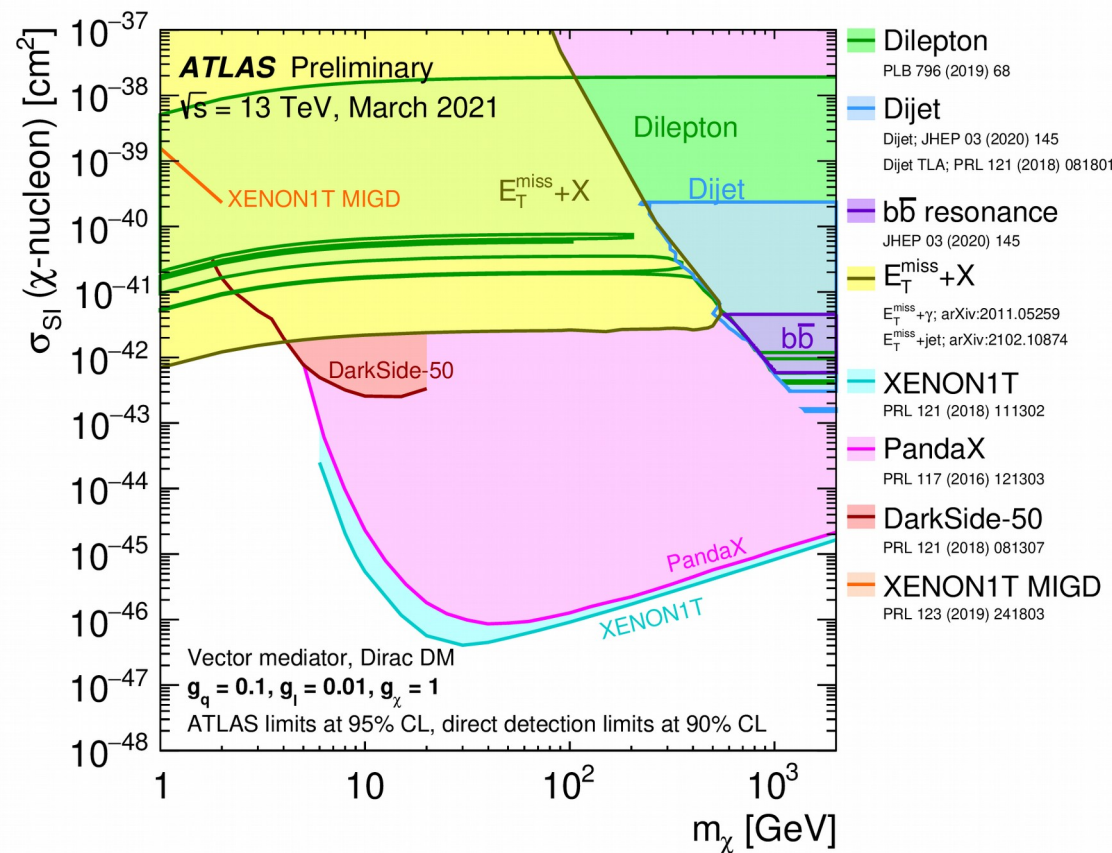
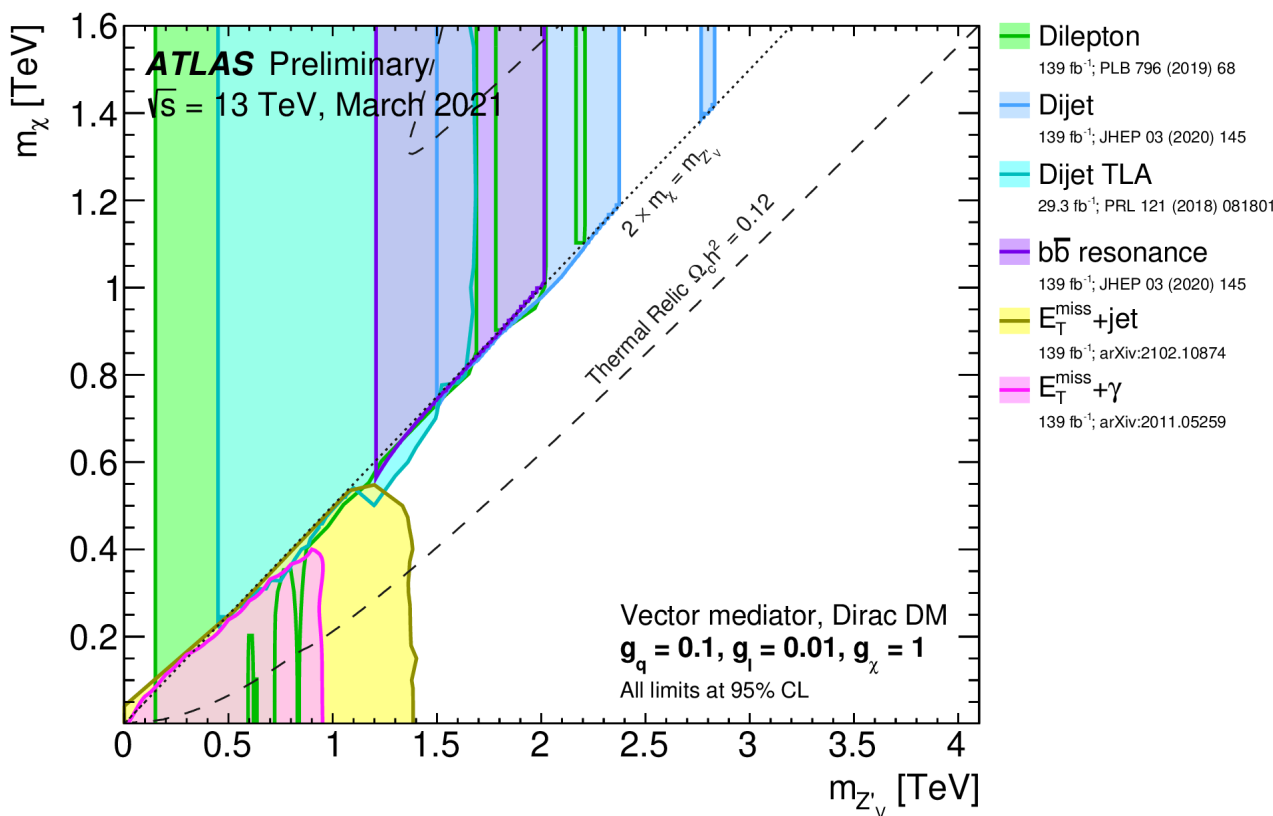
High-mass resonance search and dark matter

- > Summary plot for the simplified DM model with an axial-vector mediator



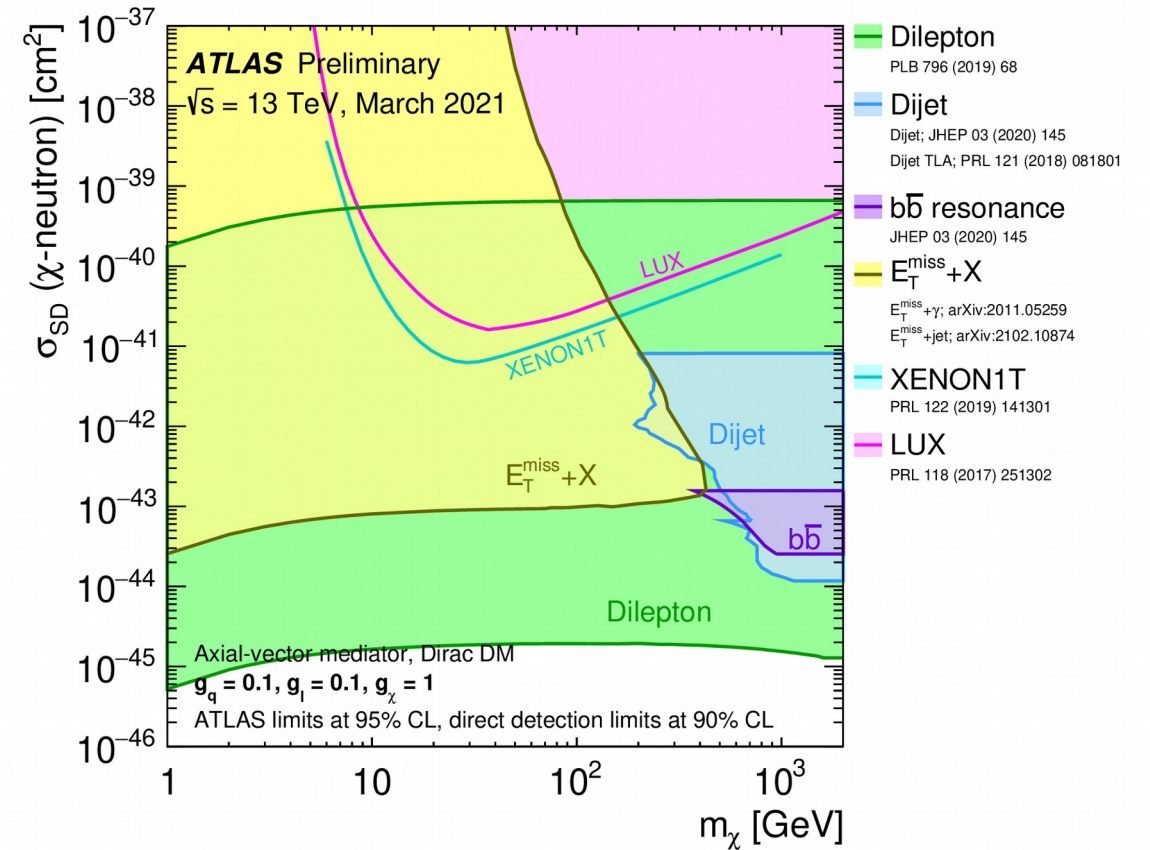
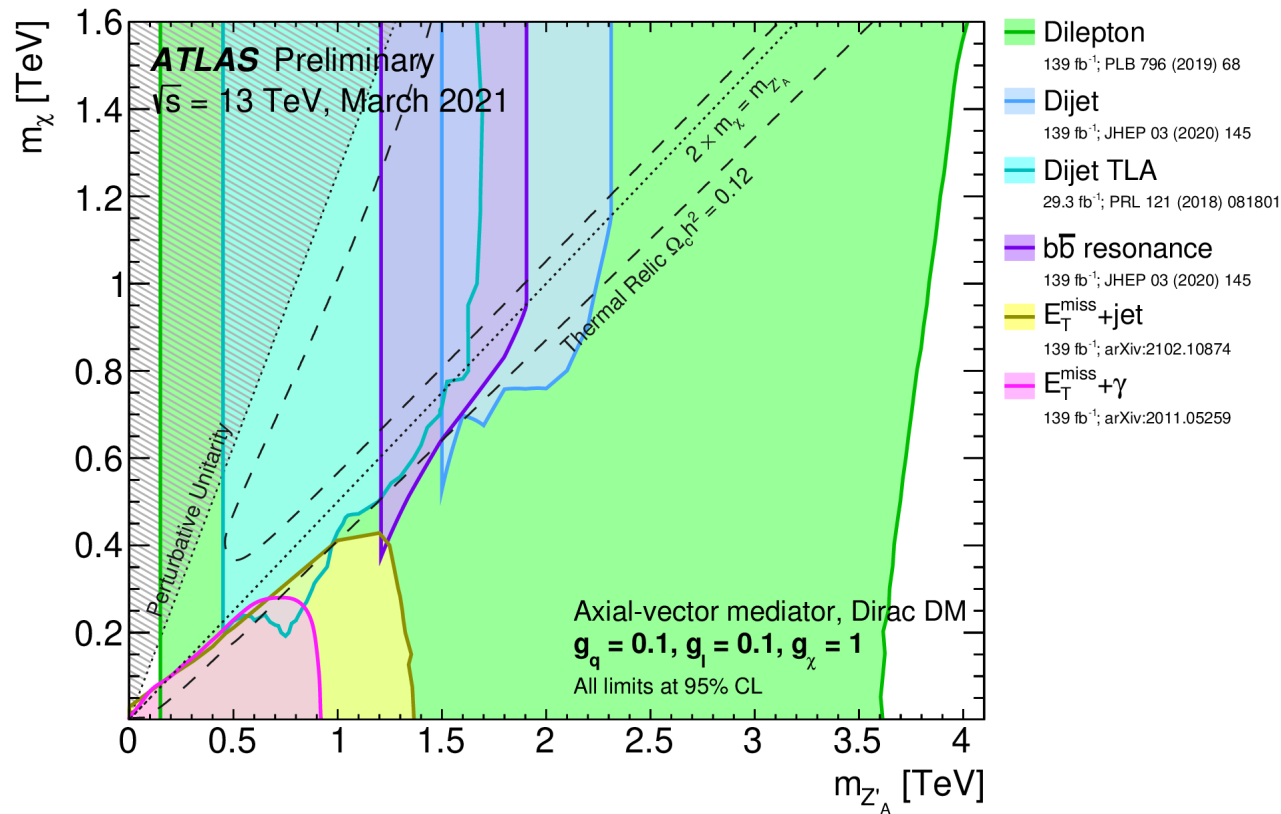
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-006/>

> Summary plot for the simplified DM model with a vector mediator



Axialvector mediators

- > Summary plot for the simplified DM model with an axialvector mediator

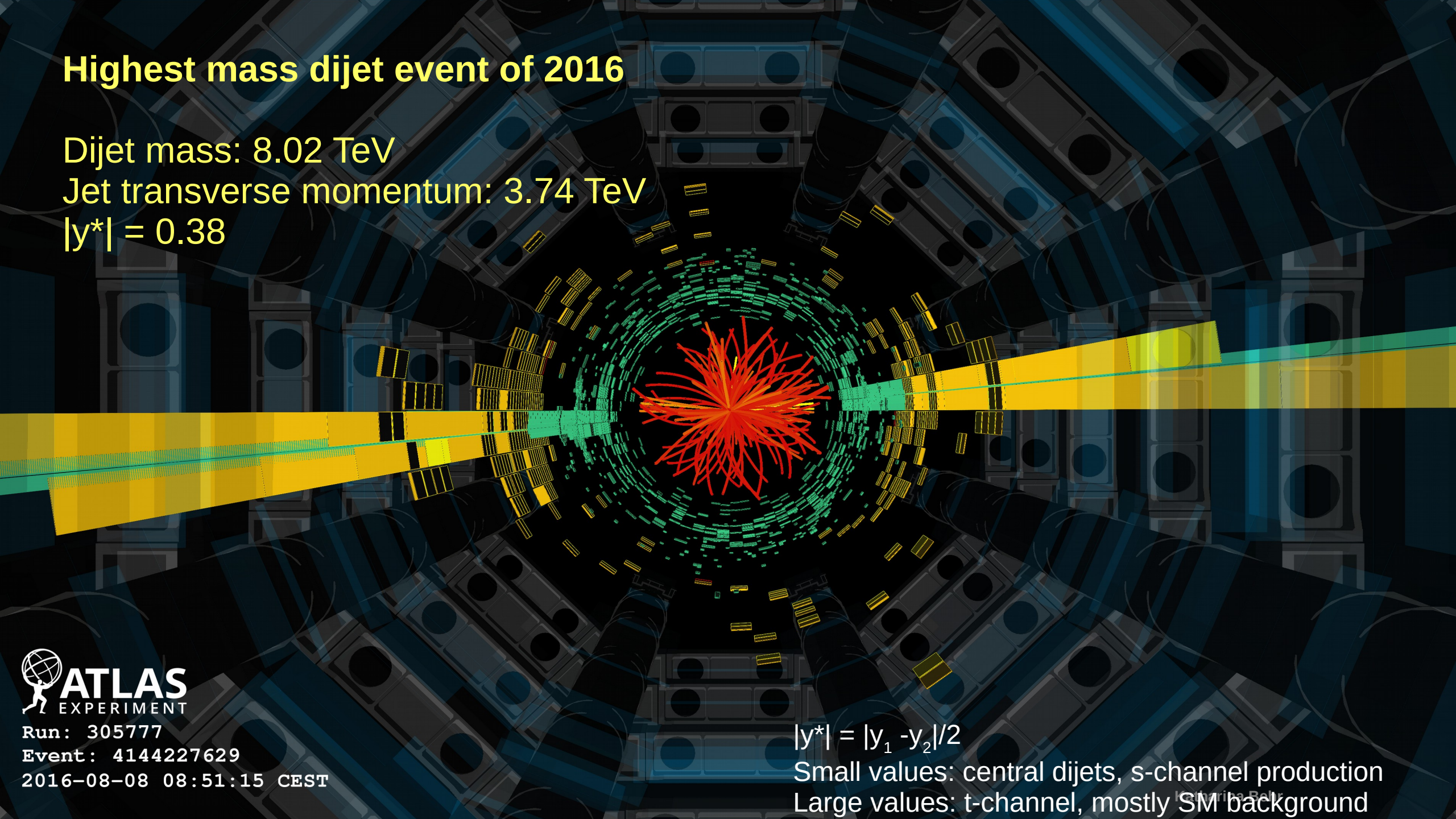


Highest mass dijet event of 2016

Dijet mass: 8.02 TeV

Jet transverse momentum: 3.74 TeV

$|y^*| = 0.38$



Run: 305777

Event: 4144227629

2016-08-08 08:51:15 CEST

$$|y^*| = |y_1 - y_2|/2$$

Small values: central dijets, s-channel production

Large values: t-channel, mostly SM background